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Hard target performance testing of non-lead, frangible ammunition

Eric Samuel Oglesby

To the Graduate Council:

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Tyler Kress, Major Professor

We have read this thesis and recommend its acceptance:

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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HARD TARGET PERFORMANCE TESTING
OF NON-LEAD, FRANGIBLE AMMUNITION

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Eric Samuel Oglesby

May, 2003

DEDICATION

This thesis is dedicated to my lovely wife,

Charissa Crossley Oglesby

who pushed me all the time to finish, even when I was stubborn and lazy

This thesis is also dedicated to my parents,

Ronald Dean Oglesby and Linda Carol Oglesby

who's constant criticism has been a motivation

to finish up school and get a real job.

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ABSTRACT

The health and environmental hazards of firing lead-containing small arms ammunition for training, sporting, law enforcement, and military purposes are well known. These dangers have prompted the development and evaluation of alternative ammunition that eliminates the undesirable aspects of lead. Any new ammunition, however, must be fully functional and provide characteristics similar to those of "standard issue" analogs to allow personnel to maintain the highest degree of proficiency in training, and to meet the many needs of protective forces, law enforcement, and the military. Numerous commercial, non-lead products are available, with many having the added feature of being "frangible", easily fragmenting upon impact with a hard surface thus minimizing collateral damage and ricochet during use.

Although most frangible, non-lead ammunition has been designed for "training," there is considerable interest in the service use of this new class of ammunition. The utilization of frangible ammunition in sensitive indoor facilities has many benefits, however, level of frangibility varies greatly thus the selection of the appropriate product can be challenging. The penetration and ricochet behavior of frangible ammunition has been and continues to be evaluated by many organizations. Difficulties arise in the sharing of results, for each user has very specific requirements, differing needs, and differing types of targets.

The purpose of this exploratory study is to summarize the examination of the impact behavior of non-lead, frangible ammunition when fired against hard targets. A variety of laboratory tests were considered in an attempt to establish a standard for assessing ammunition performance characteristics upon impacting hard targets. Current protocols for evaluating penetration and frangibility, including those employed by Department of Defense and other organizations were reviewed. New test protocols were developed to examine, both damage to the target, in addition to the nature of the impact process including fragment size and energy. Targets of interest included, but were not limited to steel, concrete, and other metal and masonry products. The results can help define "frangibility," and assist the user in the selection of the proper product for a given scenario.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

FIGURE PAGE

FIGURE PAGE

CHAPTER I

INTRODUCTION

Firing of traditional lead ammunition for training, sporting, law enforcement, and military purposes are a major source of environmental pollution throughout the United States. Lead is a significant environmental and health hazard at the numerous public, private, and government-operated shooting ranges. Non-toxic, metal matrix composite substitutes for lead have been developed at the Oak Ridge National Laboratory. High-density metals, such as tungsten, are mixed with lighter, softer metals such as tin and zinc, and consolidated employing a sinterless process to produce components with controllable density and mechanical properties. The processes of mechanical interlocking and "cold welding" bind the materials together, and can be manipulated to alter impact behavior. Bullets can be pressed directly to shape, or cores can be produced that can be swaged into projectiles, with or without jacketing.

BACKGROUND INFORMATION

Recent tests from the firing of small arms ammunition has confirmed that lead is a significant environmental and health hazard at many of the public, private, and government-operated shooting ranges nationwide. Many of the areas are contaminated with hundreds of tons of lead, the result of years of target practice and skeet shooting. Efforts have been made in the past to remediate this problem. Twelve clay target shooting ranges, at least six of which were located in wetland areas, were closed indefinitely or were required to switch to nontoxic shot products by local or state governments.[1-4] Initial investigations of these ranges were prompted by community concern for lead contamination of soils, deposition of lead shot into waters or wetlands, and ingestion of spent shot by waterfowl. Indoor ranges pose other serious concerns such as increased lead exposure to the shooter due to the enclosed space and the subsequent need for high capacity ventilation and air filtration systems. Handling of ammunition and contaminated weapons can also produce elevated lead levels in the blood by absorption through the skin.

There are many sources of lead dust and fumes generated in the firing of ammunition at ranges. The first source of lead contamination comes from the primer itself. Primers generally contain 25-30 milligrams of material, of which nearly 35% is lead styphnate and lead peroxide. Lead styphnate is commonly used as a detonator in primer components. Other sources of lead generated from firing are from vaporization. The first form of vaporization is from the heat of the explosion. The second form of vaporization is from the fragmenting of the projectile as it passes through the weapon after firing; this is caused by cylinder and barrel misalignments and due to gaps from wear and manufacturing tolerances. Temperatures generated during firing can reach up to 2000°F which causes the gases to expand creating a pressure build-up of 18,000 to 20,000 PSI in the cylinder that literally blows the dust and fumes from the weapon, much of it at right angles to the direction of fire. This is referred to as "side blast". The side blast produces a lead dust/fume cloud in the breathing zone of the shooter, whereas this increases exposure to lead dust and fumes.[5]

Damage attributed to lead poisoning on the human body has been studied by many organizations. To a shooter lead poisoning can occur through the inhalation and or ingestion of lead fumes or dust. This results in the deposition of lead in the bones and tissues of the body and alterations in normal physiological functions. No single sign or symptom may be considered as a diagnosis of lead poisoning. Lead poisoning may present such symptoms as a metallic taste in the mouth, loss of appetite, indigestion, nausea, vomiting, constipation, abdominal cramps, nervousness, and insomnia.[6] Other effects that can occur are damage to the central nervous system, the gastrointestinal system, the hematopoietic system, and the kidneys. Other organs (such as the thyroid gland and the heart) may be involved to varying degrees. In the most severe form of poisoning, profound disturbances of the central nervous system are prominent, and permanent damage to the brain may occur. Damage to the kidneys also is prominent and may be permanent.[6]

Small arms ammunition is comprised of several components; the projectile (the portion of the ammunition which exits the barrel of the firearm), the cartridge case (the portion of the ammunition which acts as a container to hold the projectile, the propellant, and the primer as a single unit), the propellant or powder (the portion of the ammunition which reacts upon firing to produce high pressure gases to propel the projectile from the firearm's barrel), and the primer (the portion of the ammunition which initiates the burning of the propellant material). Each of these components contributes to environmental pollution when the ammunition is expended. The ammunition's projectile is the major source of this pollution, since the projectile is traditionally composed of lead and/or lead and copper. Both of these elements are environmental pollutants and health hazards when introduced into the environment in either reacted (evaporated by the heat of firing) or unreacted (raw metal) forms. Reacted compounds (of lead and barium) from the ammunition's primer are a second source of pollution from small arms ammunition.

The reaction (burning) of the propellant and abrasion of the cartridge case also contribute to minor amounts of pollutants.[7]

Significant reductions in environmental pollution can be achieved through the development of ammunition projectiles that are composed of materials that are not environmental or health hazards and are economically recyclable. The Department of Energy (DOE) expends > 10 million rounds of small arm ammunition each year. This deposits over 300,000 pounds of lead and copper into DOE ranges. The DOE usage of ammunition is small compared to the civilian, law enforcement, and Department of Defense (DOD) usage, which combined, is estimated at tens of billions of rounds per year that translates into hundreds of tons of lead and copper per day. One estimate is that 400 tons of lead per day is used in the fabrication of bullets and shot in the United States alone. Much of this material (lead and copper) is never recycled or reclaimed due to cost and recoverability. At the Central Training Facility in Oak Ridge, Tennessee, which has a live fire close quarters combat training facility, nicknamed the "tire house" it costs approximately $5 per bullet to clean the bullet traps.

The bulk of small arms ammunition is expended at ranges, both indoor and outdoor. For indoor ranges, high capacity air handling and filtration systems are necessary to protect occupants from exposure. The high-efficiency filtration systems are expensive as are maintenance and waste disposal costs. For outdoor ranges, the cleanup cost of lead-based ammunition is prohibitive. There are several companies that have equipment for recovering lead shot from soil, but this equipment is designed for operation on relatively flat, dry surfaces, and there is no known practical method for recovering lead shot from forested, hilly, or marshy areas. Although reclamation of spent lead has been successfully accomplished on some target ranges, there are no regulations on the national level that require environmental monitoring or regular reclamation as part of range maintenance procedures. The Environmental Protection Agency (EPA) and the National Rifle Association encourage recovery and recycling of lead from target shooting ranges.[8] For remediation to proceed, the soil of an outdoor range must be excavated to a depth of at least four feet over the entire length and width of the range. The lead-contaminated earth must be removed, and processed as a hazardous waste. One estimate comes at a cost of about $65 per cubic foot (approximately $100 million would be needed to remediate a single 600 yard by 100 yard range at the given rate).

Currently the EPA is proposing to ban all lead- and possibly zinc-containing fishing weights.[9] Certain states have taken it upon themselves to enact new laws. "On January 1, 2000, a new law took effect that will ban the use of certain sized lead sinkers and jigs in New Hampshire's lakes and ponds. The new law will ban the use of lead sinkers weighing 1 ounce or less, and jigs 1 inch long or less. If found guilty of using lead sinkers and jigs after January 1, 2000, anglers could face a violation and fine of up to $1,000 and loss of fishing privileges for as long as 6 months."[10] Many alternative substitutes are being investigated and marketed. President Clinton and the EPA had looked into the possible ban of bullets due to environmental concerns. "New rules issued by the Environmental Protection Agency could lead to the banning of lead bullets. The EPA will investigate whether it deems lead bullets as toxic to the environment and will then consider implementing either a complete ban or partial restrictions on the manufacture of such bullets."[11] Projectiles are a more serious concern due to the vast quantities that are consumed; however, the development of replacements for lead bullets and shot is a more significant undertaking due to the more rigorous mechanical and physical demands of the application.

These issues have prompted the development and evaluation of alternative ammunition that eliminates the undesirable health and environmental aspects of lead. The ammunition must be fully functional and provide characteristics similar to those of "standard issue" ammunition, to allow personnel to maintain the highest degree of proficiency in training, and to meet the many needs for sporting, law enforcement, and military applications. Recent efforts have focused on creating projectiles using metal powders in polymer binders[12, 13] (e.g. molybdenum, [14,15] tungsten, [16] and copper in nylon), plastic or rubber projectiles, and alternate metals such as steel, [17 – 20] bismuth-tin, [21 – 23] brass, [24] zinc, [25 – 28] and tungsten-bismuth-tin (TBT) [29]. Unfortunately, these replacements have yet to meet government and military performance goals and specifications.

The concept of environmentally safe, or non-toxic ammunition has been explored in the past, but not with the vigor as seen in the last few years. At the end of World War II, projectiles for 0.30 and 0.50 caliber weapons for training and to replace lead were fabricated from tungsten, iron, and bakelite.[30] These were used for training and in special applications, however, attempts to reproduce these materials in the early 1970's were relatively unsuccessful. In addition, the use of bakelite, some grades of which are fabricated from phenolic-formaldehyde mixtures, has experienced a decline as new inexpensive polymer materials are developed. Frangible, non-toxic projectiles are also employed as training ammunition in place of large caliber, high velocity, kinetic energy penetrators.[31] The simulated projectiles must exhibit similar flight characteristics as the actual penetrators, however, ideally self-destruct in flight or on impact for safety reasons.

Generally, a partially densified iron powder component encased in a low-strength, thermally-degradable plastic container is used. These replacements fail on light impact or after heating in flight thus meeting range safety requirements.

More recently, replacement projectiles for training and certification of personnel have been fabricated from molybdenum, tungsten, copper, and brass powders in a nylon matrix.[32, 33] The projectiles are formed employing injection molding techniques and ammunition in different calibers are being marketed by a number of companies. The ammunition is functional and acceptable for many applications; however, the density of the copper and brass nylon bullet materials are much less than that of the lead components (5.8 vs. 11.3 g/cm^3). The low weight of the projectile may cause problems in weapon functionality and accuracy, especially at extended ranges. In addition, only the powdered metal portion of the components can be recycled. The plastic binder is a consumable that must be removed, likely through incineration, before the metals can be reclaimed.

The Molybdenum/polymer bullet[14, 15] is a blend of biodegradable polymers and powdered molybdenum which results in a shot (Molyshot) that closely resembles lead in its physical and ballistic properties. Molyshot is manufactured by drawing an extrudable plastic mass of the blended material at high temperature into a wire and moulding it between rollers to produce rounded shot of chosen sizes, the densities and hardness of which are very close to those of lead and bismuth-tin. Chronic oral ingestion of molecular molybdenum can be toxic. Adverse effects include growth retardation, anemia, bone deformities, and interference with copper metabolism.

The first attempts at producing and marketing a tungsten/polymer shot[16] were carried out by Eley Hawk in England. Their product (Eley Black Feather Cartridges), launched in 1990, caused considerable initial interest. However, problems including pellets breaking up or coalescing, poor patterning, and very high cost ultimately resulted in the product being withdrawn from the market. Recently Elastomer Engineering of Cheshire, England, claims to have overcome the original difficulties. Their tungsten/polymer shot is made using powdered tungsten in a thermo-plastic polymer (made from food-grade raw materials) and can be produced to have a density equal to that of lead.

Another solution is the replacement of lead with other metals such as steel, brass, bismuth-tin, zinc, and tungsten-bismuth-tin (TBT). Steel shot is required for hunting waterfowl in many areas.[17 – 20] Due to high hardness and low density of the metal, which is 70% the density of lead (7.8 vs. 11.3 g/cm^3), steels are less than desirable choices for use as projectile materials. There is no doubt that the ballistic properties of lead and steel shot differ. Steel shot pellets are about 30% lighter than lead pellets of the same diameter and are significantly harder than lead pellets. These basic physical differences result in less pellet deformation, denser patterning, shorter shot strings, and a lower retained velocity/energy at long ranges for steel shot compared with lead shot. However, the development of modern steel shotshell ammunition has evolved to the point where the perceived deficiencies of steel have been largely overcome. Steel shot has caused intense controversy for it is believed that due to its reduced ballistic properties, many birds are being wounded and maimed, dying gruesome deaths. The ultimate effect might be that increased losses of birds through crippling would surpass the number of birds saved by the elimination of lead poisoning.

Bismuth and its alloys have also experienced much popularity as replacements for lead. Bismuth-tin shot[21 – 23] is currently available, but again the density of this metal is only 86% of that of lead (9.8 vs. 11.3 g/cm^3), and again this creates concerns with regards to ballistic performance. Pure bismuth, used in the original bismuth cartridges, is brittle, causing pellets to break in the gun barrel, leading to poor patterning, and causing pellets to shatter on impact. However, the addition of approximately 3% tin and modifications in the production process has reduced shot brittleness, resulting in improved performance. Because bismuth-tin and lead have similar densities and softness, shotshell gauges, chamber sizes, and barrel designs suitable for lead may be used without modification with bismuth-tin cartridges.

The advantages of zinc[25 – 28] as a metal for shot manufacture are that it is plentiful and has satisfactory ductility and hardness. However, it is relatively expensive compared with either steel or lead, and it has relatively poor ballistic qualities because of its low density (7.13 vs. 11.3 g/cm^3). Zinc shot is apparently effective for hunting over short shooting distances. Unfortunately, zinc shot (and other forms of zinc metal) can be toxic to wildlife when ingested, although its toxicity is lower than lead.

Tungsten/bismuth/tin (TBT) [29] shot is still in the research and development stage. TBT is produced by mechanically suspending finely powdered tungsten (39%) in a combination of molten tin (16.5%) and bismuth (44.5%). The resulting shot pellets have a density and hardness virtually identical to that of lead. Initial toxicity tests on mallards dosed with up to 17 pellets indicate little or no tissue uptake of the constituent metals and no toxic effects. Should this sort of shot become commercially available, it would probably be priced somewhat higher than bismuth-tin shot due to a more complex production process.

PURPOSE

The purpose of this exploratory study is to summarize the examination of the impact behavior of non-lead, frangible ammunition when fired against hard targets. A variety of laboratory tests were developed in an attempt to establish a standard for assessing frangible ammunition performance characteristics upon impacting hard targets.

Current protocols for evaluating penetration and frangibility, including those employed by Department of Defense and other organizations were reviewed. Most of the tests are qualitative in nature, and many different methods are involved. This makes comparisons difficult or impossible.

New test protocols were developed to examine both damage to the target, in addition to the nature of the impact process including fragment size and energy. Targets of interest included, but were not limited to steel, concrete, and other metal and masonry products. Part of the new testing protocol was to set up a rudimentary design of experiments to look at as many different bullet variations as possible, in an attempt to gather as much data as was possible in the given time frame. This was a very simplistic approach that would hopefully start to unlock the "frangible" mystery. Frangibility is advantageous, however the question, "How frangible?" must be addressed.

There is not much information relative to the subject of quantitative frangibility in the open literature. Much of the background for this study came from military studies done throughout the years and from research done at Oak Ridge National Laboratory

(ORNL) over the past few years. Much of the research done outside of these two areas has been in the area of hypervelocity impact dynamics. Some of this information was helpful in understanding the damage profile generated by bullets and other shaped projectiles during impact.

DOE has been involved in the development of non-lead frangible rifle and pistol bullets, which are composed of materials that do not pose significant environmental or health hazards and which are economically recyclable. The primary objective of this government program was to develop a non-toxic projectile for use in training of security personnel and for field application. The bullets were to meet all performance specifications of currently acceptable bullets, but significantly reduce or eliminate exposure of the shooter to hazardous materials, and minimize the release of toxic materials into the environment. The use of a frangible projectile that disintegrates upon impact reduces damage to training facilities, lowers the risk of ricochet and thus personal injury, and permits the use of a broader range of weapons in situations where over-penetration is a problem (e.g. inside a nuclear reactor or hazardous waste storage facility).

DISCUSSION OF "FRANGIBILITY"

When a bullet impacts a hard target, the bullet ricochets from the target surface. The inherit danger posed to the shooter then is which direction is the bullet going when it ricochets from the target. Another concern is back splatter from the breakup of the projectile after impact. If the bullet's particles are of significant size, the shooter can be in danger of being struck at various points on the body by numerous fragments. At a number of DOE facilities, hazardous waste and radioactive material are stored in regular metal containers around the sites. One primary concern of this study was to decrease the risk of security forces shooting holes in these containers if a gun battle was conducted against adversaries near these containers. This was accomplished by changing the bullet's hardness, design, velocity, and energy. An area of concern with the new frangible rounds is how big are the particles from an impact of the bullet on a hard surface? Can they do excessive damage to unintended objects near the target? What effect will they have on personnel close by, or storage containers near to the bullet's point of impact?

According to *New American Standard Dictionary,* frangible is "easily broken" or "breakable, brittle, fragile".[34] "Frangibility" is a nebulous term with a variety of perceived meanings. Current protocols and procedures used by bullet manufacturers and the military fall short in defining a series of tests that conclusively define frangibility on a quantitative basis. Much of the testing done so far is qualitative, with no way to correlate data from one test to the next.

Frangible ammunition is terminology that has many individuals in the military, government, and industry scratching their collective heads. When "frangible" is spoken in industry circles, heads start shaking about the validity of the term.

Numerous methods have been used to test frangibility. Some tests that have been used are as follows:

- Naval Sea Systems Command (NAVSEASYSCOM) defined frangibility as ... not able to penetrate ¾ in. plywood at a distance of 10 ft. after the bullet has passed through a 1/8-in. cardboard silhouette.[35]

- Aberdeen Proving Ground looked at the residue recovered and the condition of a cardboard cover after firing 5.56mm & 9mm against 12.7 mm mild steel plate at 35 m. [36]

Some designers of frangible ammunition have used qualitative tests to describe their frangible ammunition.

- How many sheets of marine grade ¾ in. plywood or 5/8 in. sheet-rock on 3.5" centers will the bullet penetrate?
- Frangible bullets should be able to penetrate body armor but not cause significant damage or injury after passing through ¾ in. plywood or two sheets of 5/8 in. drywall placed 3-½ in. apart.
- Frangible bullets turn to dust upon impact with a hard surface and will not ricochet thus limiting collateral damage.

The main problem with these tests is the fact that there are differences between "frangibility" and "controlled penetration". Frangibility is a generic term describing the ability of a projectile to break apart upon impact, controlled penetration is a term that defines the ability to control ricochet & penetration characteristics and terminal performance..

The desire for a non-lead frangible round has shown increasing interest in many areas of military and civilian police divisions. Having a round that is suitable for both training and tactical purposes is a welcome addition to their arsenals. The Army is a prime candidate for this research because of the recent shutdown of many Army Reserve indoor training facilities. This was enacted due to the lead contamination and poor ventilation in the facilities. Instead of cleaning the facilities it was deemed less expensive to just shut down the ranges. With the shutdown of their local indoor range, many reserve bases have to transport personnel to sanctioned training facilities to get weapons qualification.

Civilian police departments could also benefit from this new technology based on terrain conditions in metropolitan environments, or big cities. Not having to worry about civilian casualties from an errant shot at a fleeing suspect would decrease the risk in shootout situations. In defense situations, a highly delivered bullet generally results in the ability to penetrate obstacles and clothing. In urban law enforcement situations, it can cause problems with penetration of walls, ceilings, and floors putting innocent people at risk. A powdered tungsten core will have a greater tendency to break up after impact, but still deliver its energy efficiently to the intended target. Since the material is non-toxic, the contamination after-effects of firing many bullets into an area are virtually non-existent. Since tungsten cores are more dense than lead, less volume of material is required for the same energy delivery, and there is less secondary missile material, broken into far smaller particles, reducing the chance for unnecessary collateral damage. This type of round would be perfectly suited for an incident that occurred on February 28, 1997. Two suspects attempted to rob the Bank of America branch in Los Angeles, California. The suspects had the police outgunned with AK-47's and SKS rifles. On their escape route the suspects wounded 16 civilians and police officers. Nine elementary schools were shut down and the surrounding area had to go into a lockdown until the situation was resolved.[37] The police needed a bullet that had the capability of stopping their suspect, but at the same time not endangering any bystanders from a shot that might ricochet.

DAMAGE INDEX

The need for a ranking criterion for "frangible" ammunition is a subject that is widely debated among people in the ammunition industry and military service. Most testing that has been done on frangible ammunition has been qualitative, which relies on the tester to somewhat subjectively determine how a bullet performed under their testing conditions. Much latitude exists for discussion on techniques and analysis of results. It would be desirable to develop a more analytical approach, which will quantify results based on a set of criteria developed during experimentation. This will hopefully provide a starting point for developing a consistent methodology for evaluating different combinations of bullets.

In dealing with hard target damage a few principles were brought to the forefront during the course of this work. The first principle, discerned from the data gathered, related penetration depth to cross-sectional area. Generally speaking, the deeper it goes, the bigger the hole. This concept is not so spectacular, but after looking at penetration depth and cross-sectional area of the bullets tested and calculating volume, it holds true. The second principle is based on the kinetic energy of the bullets. Although a bullet may have a high kinetic energy, bullet construction and material play a major factor in the bullet's damage ability. The ability of the target to de-energize the projectile is also a concern based on the situations, which the tests were constructed under.

To fully appreciate the results one must look at the principles that are involved. Using basic dynamics principles of kinematics and Newton's second law, a damage index number could be attributed to the bullet's performance. The extent of the damage can be attributed to a variety of factors such as construction of the bullet, material properties, mass, velocity, etc. The purpose of the damage index was to try to encompass all of these properties into a guideline, that when looked as a whole, gave an overall performance of the bullets tested.

Numerous attempts were made to try and incorporate all the data into one or two equations that would explain the bullet's damage profile. This proved to be a daunting task, which was unsuccessful. It was the author's sincere hope to come up with a working equation that could then be used to correlate this work. With a working equation, the author hoped to immortalize his work in textbooks and journals for future reference. Because of the failed attempt at obtaining one equation, the author's search for immortality must now shift to other areas. Perhaps, like Sisyphus, this search will continue for an eternity.

In looking at the impact behavior, the work done by the bullet plays a part in the damage profile. The first step in determining the work done by the bullets on a target was to determine the acceleration of the bullet as it traveled toward the target. The equation used for acceleration is: $a = v^2 \div 2x$. Where a is the term for acceleration, v is the term for velocity, and x is the term for distance. During this study all distances to targets was kept the same at 10 feet. A chronograph set up near the point of impact measured velocity. Testing was done outdoors with no wind evident, so air friction was determined to be negligible in the short distances that the shots took place. In an ideal situation, these tests would have been done indoors in a closed environment, but circumstances prevented this. The second step was to look at the force of the bullet just before it impacts a target. Kinetic energy was first calculated to see just how each bullet performed, but this does not give an accurate representation in regard to work done. The force was calculated by Newton's second law which is: $F = (m \times a) / g_c$. Where *F* is the term to denote force, *m* is the term for mass of the object, *a* is the term for acceleration, and g_c is the term for gravitational constant. The gravitational constant had to be put in due to the using of U.S. units in the equations. The third step was to calculate the work done by the bullet as it impacts the target. The equation for work is: $W = F \times d$. Where *W* is the term to denote work, *F* is the term for force, and *d* is the term for distance. The distance represented is the penetration depth of the bullet, which was determined after analyzing the bullet impacts using the Rodenstock machine. The work done by the bullet gives a better representation of the potential to create surface area and the ability to break up the bullet upon impact.

After plotting and analyzing the work, it was found out that the same general curves were evident, which were found in the kinetic energy graph, penetration depth graph, etc. This suggested that something was missing in the analysis. After deliberating with my mentor, it was determined that the key to all of this was more than likely in the bullet's toughness. The toughness helped explain the differences in material properties that made up the assortment of bullet's tested.

After looking at the materials used in the bullets in this test, a method had to be employed to evaluate the different results, which were recorded. There are two main types of fractures involved in materials failing, brittle and ductile. A brittle material is easily broken, low yield strength before fracture. A ductile material is less apt to come apart, higher yield strength due to plastic strain. Based on these two material properties, fracture energy had to be looked at. Flinn and Trojan explain fracture energy as follows:

"To fracture a material, work must be performed. This work is required to supply the energy needed to create the fracture surfaces and to plastically deform the material if local yielding occurs prior to fracture. This "energy-balance" approach to fracture can be summarized as:

Energy input (work) to produce fracture	$\geq$	Surface energy (γ_s) of fracture surfaces	+	Energy of plastic deformation (γ_p)

Here γ_s is the surface energy per unit surface area, and γ_p is the energy of plastic deformation per unit volume. The energy input is the difference between the external work supplied and the stored elastic energy at the onset of fracture."[38]

This information helped to explain the differences in energy available by the different bullets and damage done by the bullet to targets. The energy that was available had to overcome the bonding of the bullet's design to fracture the bullet. The goal was to fracture the bullet before it deformed the target.

The toughness, strength of the material, and the ability of the material to be torn apart is one of the key ingredients that comprise the aspects of a good frangible bullet. After defining what makes a good frangible round, the particles generated upon impact must be looked at. Just because a bullet breaks up when it hits a target doesn't make it a good frangible round. The size of the particles must be examined to see number of particles generated, and the size of the particles.

The second part of the damage index involved the particles generated by the bullets during the second phase of testing. This involved capture of particles after striking a piece of armor plate with a gelatin donut ring attached. This is a painstaking process involving time for preparation of the gelatin, and subsequent analysis after dissecting the rings and weighing the particles after pouring through a series of sieves. This analysis gives the user an understanding of the bullet's frangibility after impacting targets. Although this analysis is qualitative in nature, solely based on the examination of the residue generated after impact. This information is helpful in determining how many particles and their weights are not just turned to dust, and could still cause harmful damage to anyone caught nearby after their initial impact. To fully understand the bullet's performance, one must look at many small parts of information to understand everything that encompasses the damage.

The remainder of the thesis is organized as follows:

Chapter II: Experimental Procedure and Test Methods

Chapter III: Test Results

Chapter IV: Discussion

CHAPTER II

EXPERIMENTAL PROCEDURE

The purpose of the present investigation was to develop a quantitative value for the performance of non-lead, frangible ammunition. The choice of materials for developing a less toxic material for replacing lead is driven by many factors including the physical, mechanical, and thermal properties and toxicological concerns. Another major consideration is cost. A review of potential constituents was conducted and a list of candidate metals assembled (Table 1). The process requires a high-density metal that is to be encapsulated in a softer, typically lighter metal. When consolidated, the resulting compact or composite is to perform in a manner similar to lead. Tungsten was selected as the high-density component with tin as the binder. Through experience and a review of the environmental and toxicological information regarding the materials in Table 1, many of the candidate metals were disqualified. Emphasis in this effort was thus placed on the tungsten-tin composition, a mixture of materials that has performed well in processing studies and preliminary testing.

It was found that the M-70 grade of tungsten powder, supplied by Osram Sylvania of Towanda, Pennsylvania was optimum for blending with the selected binder material, and for the cold pressing of cores.[39] The tin powder was procured from Pyron Metal Powders (formerly Greenback Industries) of Greenback, Tennessee. The TC-125 grade of Sn powder was used in this study.[40]

Table 1. **Properties of Materials**

Material	Symbol	Density (g/cm^3)	Strength (MPa)	Hardness (VHN)	Approx. Cost ($/lb)
Lead (99.94%)	Pb	11.35	13	0.049(3HB)	0.43 – 1.00
Lead + 5% Tin	Pb/Sn	11.00	23	8 HB*	
Lead + 4% Antimony	Pb/Sb	11.02	100	8.1 HB*	1.00 – 2.00
Copper	Cu	8.93	200	0.50	
Bismuth	Bi	9.81	NA	0.095	
Gold	Au	19.30	100	0.65	4,200
Silver	Ag	10.49	125	0.94	66.00
Platinum	Pt	21.45	140	0.86	> 5000
Aluminum	Al	2.70	45	0.25	0.75
Tungsten	W	19.25	3450	3.43	10.00 – 15.00
Tin	Sn	7.29	15	0.071	3.50 – 5.00
Iron	Fe	7.87	600	0.65	< 0.10
Molybdenum	Mo	10.22	500	0.38	
Tantalum	Ta	16.6	360	---	
Low Carbon Steel	Fe-FeC	7.5	350	90 HB*	< 0.10
Zinc	Zn	7.13	150	0.20	0.65 – 1.55

* As noted, the hardness of lead is 3 HB in similar units

BULLET FABRICATION

The cores for swaging into the bullets were fabricated using simple powder metallurgical techniques. One-kilogram batches of powder were dry blended for 15 minutes with no lubricants or added binders in a 16-quart V-blender equipped with an intensifier bar. The powders were stored in 500 ml plastic bottles. The powder for each core was individually weighed on a laboratory scale with 0.02-grain resolution. Cores were pressed at room temperature. The premeasured powder was poured into the core die and compacted simultaneously from top and bottom using an Enerpac tabletop hydraulic press. (Figure 1).

The press is a simple H-frame unit with a 1.5-inch hydraulic ram and 6 inches of travel. An electric hydraulic pump capable of 5,000 psi supplies pressure. The dies and punches were set on a spring-loaded table to allow the punches to float and thus compact the cores from both ends. The double action produces more uniform compaction.

These cores were then swaged into final form. Unjacketed bullets were swaged in a single step using a hand press and a ¾-E point form die. An unwashed core was placed in the die with hemispherical cap toward the ogive part of the point form die. Spacers were used to properly position the die and ejection pins, and ensure formation of an acceptable bullet nose. A punch the same diameter of the bullet and die cavity was used to apply pressure (Figure 2).[41] Most of the bullets in this study were unjacketed to better assess frangibility without interference of a copper alloy container.

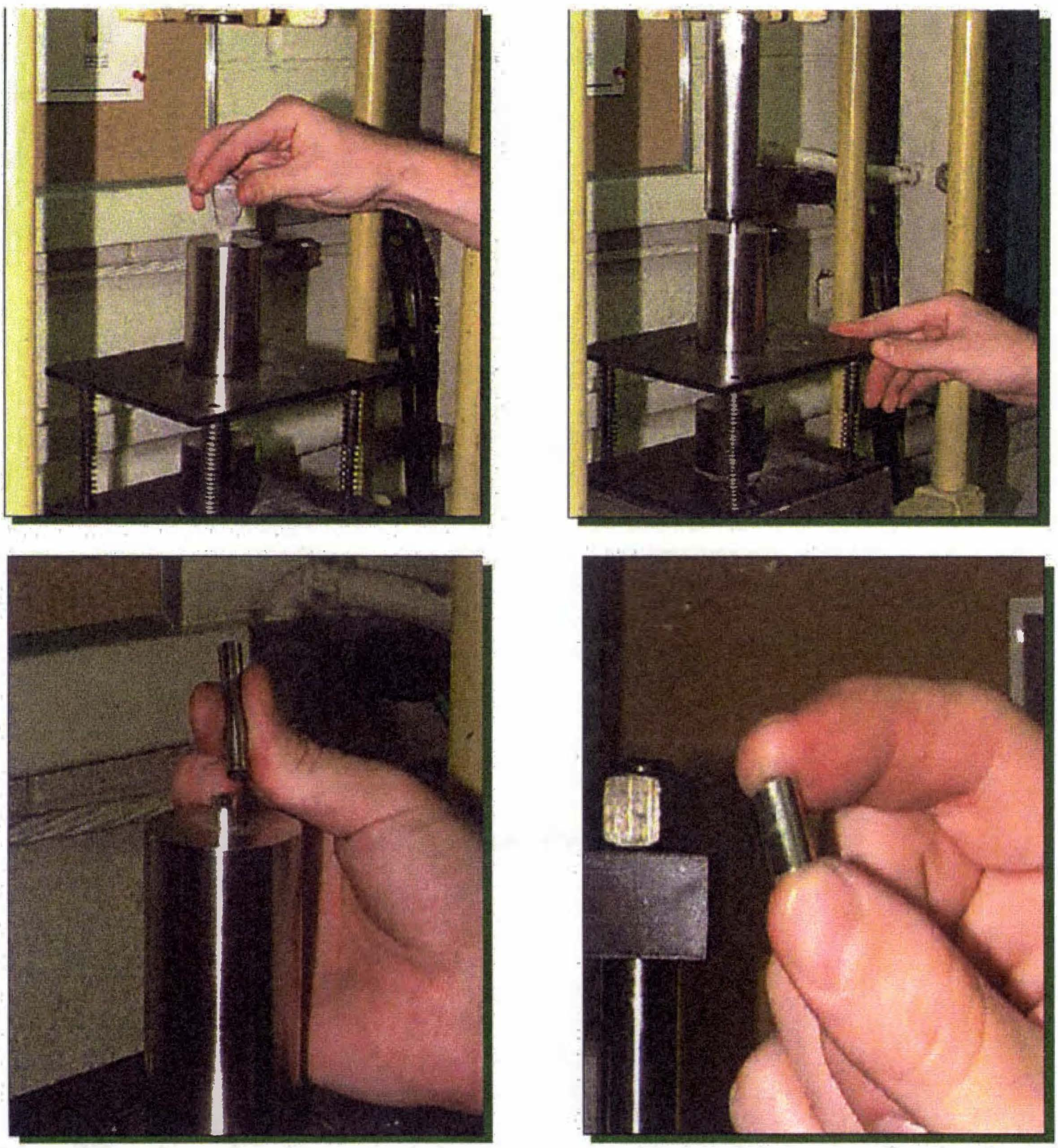
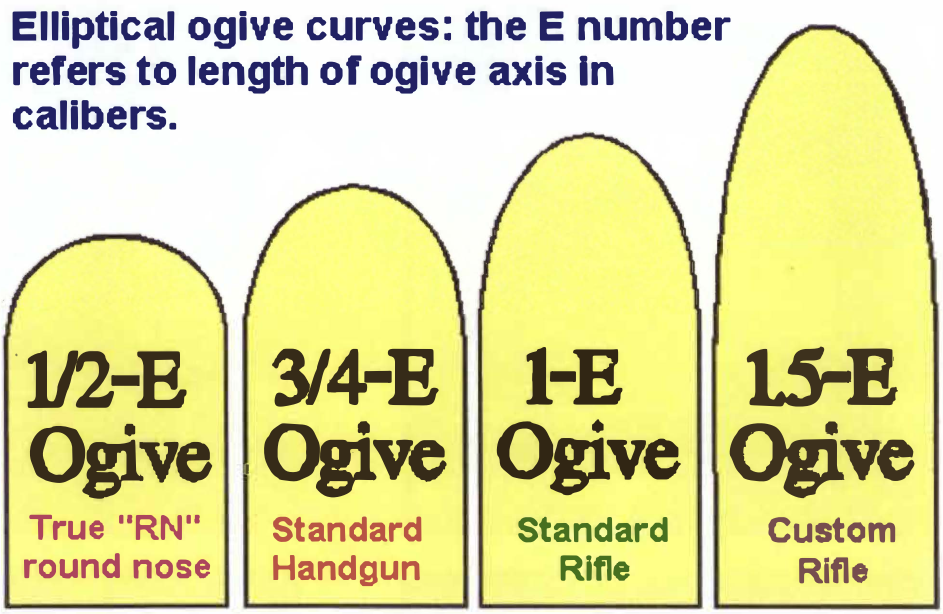
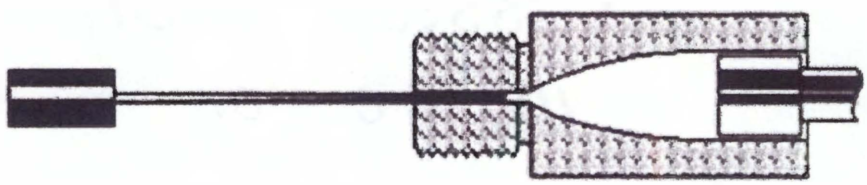


Figure 1. Bullet Core Fabrication





Example of Punch Die used in study.
The internal punch slides up and down inside the die, to eject the bullet and seal the threaded end of the die. The external punch pushes the material into the die, applies pressure, and is removed so the bullet can be ejected.

Figure 2. Bullet Ogives and Punch Schematic

The composition of the cores was selected to mimic the density of lead. In this study, tin was used as the lighter, softer binder metal, with tungsten as the high-density phase. A rule of mixtures approach was utilized to determine a starting composition. The rule of mixtures relates the property of a combination of materials to the volume fraction of each phase in the composite or:

$$V_1X_1 + V_2X_2 + \ldots + V_nX_n = X_{composite}$$

Where V is the volume fraction of the specified material and X is a property such as density, modulus of elasticity, etc. In this case, the volume fractions of tin and tungsten were calculated from:

$$V_W\rho_W + V_{Sn}\rho_{Sn} = \rho_{composite}$$

where ρ is density, and the chosen values for W and Sn were 19.25 and 7.35 g/cm^3, respectively. This assumes no chemical interaction (e.g. alloying), which would not be expected for room temperature processing.

This study focused on testing 9mm non-lead, frangible bullets. After tests were developed to measure the frangible bullet's performance, a variety of non-lead, frangible bullets were manufactured at Oak Ridge National Laboratory, to test as many variations as possible. Five groups were chosen as the main variables for testing. Within each group, variations were made to get as much information in each test. A list and description of the bullets used in this study is given in Table 2.

Table 2. **Bullets Tested**

Bullet Type	Density (g/cm^3)	Bullet Weight (Grains)	Propellant
Vary Energy (Mass)			
WSn 0100	7.30	86.01	3.3 gn 231
WSn 2575	8.64	99.46	3.6 gn 231
WSn 3961	9.64	111.04	3.65 gn 231
WSn 5248	10.79	124.00	4.0 gn 231
WSn 5941	11.53	132.53	4.0 gn 231
Vary Velocity			
WSn 5248	10.79	124.00	3.5 gn 231
WSn 5248	10.79	124.00	4.0 gn 231
WSn 5248	10.79	124.00	4.5 gn 231
WSn 5248	10.79	124.00	5.0 gn 231
Different Binder			
WSn 5248 Fine Sn	10.79	124.00	4.0 gn 231
WSn 5248 Standard	10.79	124.00	4.0 gn 231
WSn 5248 Sn Tailings	10.79	124.00	4.0 gn 231
Commercial Frangible Ammunition			
Simunition	N/A	85.00	N/A
Delta/Winchester Ranger	N/A	83.00	N/A
Lead Rounds			
Swaged Pb	11.34	125.00	4.0 gn 231
Hard Cast Pb	11.34	125.00	4.0 gn 231

ASSEMBLING AMMUNITION

After all non-lead, frangible cores were manufactured in the laboratory, the process of making the actual complete bullet was undertaken. There are numerous steps involved in properly assembling ammunition. Instead of using brass that had already been shot and cleaned, new brass was bought from Remington to insure repeatability in the reloading process, and to cut down in the cleaning process associated with used brass. Steps in assembling ammunition are described in Figure 3.

TEST METHODS: IMPACT DAMAGE & PROFILOMETER MEASUREMENT

A variety of bullets were evaluated in the preliminary "proof" testing. Variables such as bullet mass, velocity, tin binder, and bonding were explored. The WSn bullets are tungsten-tin powder metal bullets where the number defines the composition. For example, WSn 5248 designates a bullet core composed of 52-wt. % tungsten and 48-wt. % tin. This terminology is consistent throughout this study.

A standard reference length was determined using the 124 gn. unjacketed 9mm bullet made from the WSn 5248 mixture. The reference length was used to calculate the volume needed to achieve the same length but with different densities. Different bullet compositions were fabricated to examine changes in mass without altering volume. Bullet weights of 86 to 132 grains were manufactured, with compositions ranging from pure tin (WSn 0100) to WSn 5941. Propellant charge was varied to keep velocity constant.

All brass has to be resized to allow a bullet to be seated in the case. The resizing allows the user to crimp the bullet slug later on ensuring a proper fit. The picture on the left shows the threading of the sizer die into the press.

With the press handle in the uppermost position slide the case into the shell holder.

Pull the press handle all the way to the bottom and run the case all the way into the sizer die. This step resizes the case to the proper dimension and sets the case neck diameter to hold the bullet tightly.

After sizing the case neck to the proper caliber, case length must be checked and trimmed if necessary to ensure proper length for proper chambering and for safety reasons.

Figure 3. Step by step instruction for assembling ammunition

After cases have been trimmed they need to also be chamfered and deburred. This will remove any burrs left on the case after trimming and will allow a new bullet to be easily seated into the case.

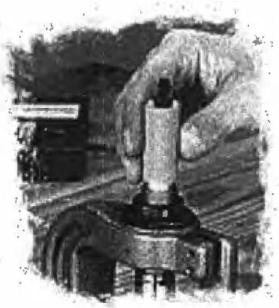
Since most cases are straight-wall by manufacture design, they must be expanded in a separate expander die. The expander will bell outward the case mouth just enough to accept the bullet being swaged later on.

All bullets must have a primer inserted into it. This primer is the combustion starting point of the explosion that fires the bullet. Primers are placed in the green tray face up and the bullet is inserted into the top of the device. By pulling the handle a primer is seated into the bullet.

Figure 3. Continued.

Powder dispensing is the next step, which measures out the propellant used in the bullet. The propellant used in this study was Winchester 231, which Mr. Lowden uses on a regular basis. Using his knowledge of reloading and the SPEER reloading manuals to determine the different charges needed to change velocities for each of the tests and keep velocity the same while using different bullet masses.

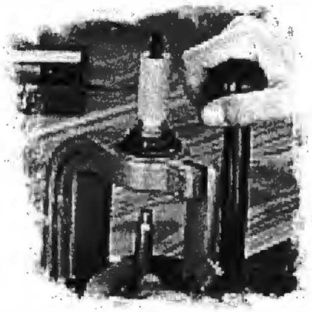
After accurately weighing out the powder charge, the powder was poured into each case. Each tray was marked to ensure that when the bullet was seated into the case, it matched up with the proper bullet for the experiment.



The last step in the bullet assembling is setting up the bullet seating press. To set up the press, you must put a case in the shell holder and lower the press handle, this rams the case to the top of the press stroke. The seater die body is turned down until it stops. The crimp shoulder in the die is now pressing against the top of the case mouth. By backing the die out one turn, this raises the crimp shoulder just above the case mouth.

Figure 3. Continued.

Next, unscrew the seater plug enough to keep the bullet from being seated too deeply.



With the handle in the uppermost position, insert a properly primed and charged case into the shell holder.

Taking a bullet and holding it over the case mouth with one hand you pull the press handle down easing the case and the bullet up into the die. After raising the handle, you must check the bullet to make sure that the seating depth is the right length. If it is not, simply change the plug up or down and do the step again.

Figure 3. Continued.

In another series, bullet weight was held constant while velocity was changed. Using a WSn 5248 124 gn unjacketed 9mm bullet, as a reference bullet. Propellant charge was varied in increments of 0.5 gn during loading of the ammunition. This was used to evaluate the effect of constant mass with different velocities on the kinetic energy of the bullet during testing.

The influence of binder particle size on frangibility was also investigated, by developing two rounds in the WSn 5248 124 gn package. The first round is a composition of fine Sn, which is a fine dense powder. The second round utilized Sn Tailings, which is a coarse blended powder. The different binders were used to look at the performance of the bonding of the three tin compositions in this study.

Two commercially frangible rounds were included for comparison. The first was the Simunition Greenshield, which is an unjacketed 9mm 85 gn copper polymer compound. The second is the Winchester/Delta Ranger, an unjacketed 9mm 83 gn unjacketed tungsten copper mixture bonded with nylon.

Two different lead rounds were included to compare frangibility and damage to target. The two rounds tested were both unjacketed 9mm bullets. The first was a Swaged Pb bullet and the other was a Hard Cast Pb bullet. Both of these bullets represent two different techniques of producing bullets. Both have their advantages and disadvantages. In terms of cost of equipment, casting for a particular bullet weight and shape starts out being cheaper. The limiting factor is when the shooter starts experimenting with different weights and shapes. This means that another mold must be purchased to accommodate for the new design. Swaging lets the user make an almost unlimited number of different weights and styles of bullets.

Part 1: Impact Damage

Two important aspects of frangibility are damage to target, size of particles, and remaining energy for the particles that are produced upon impact. These characteristics were examined using a variety of techniques. To evaluate target damage, five rounds of each type bullet were fired at 1018 mild steel plates as shown in Figure 4.

Initial testing was accomplished firing a 9mm P226 Sig Sauer pistol in a Ransom Rest™ at ½" thick 1018 mild steel plate at a distance of 10 ft. Pictures of the set-up are shown in Figures 5-8. Velocities were recorded with a chronograph near the point of impact. A chronograph is an instrument that registers or graphically records time intervals such as the duration of an event.[43] The chronograph used in this study has two sensors spaced apart with shields on top of them, as shown in Figure 7. When a bullet is fired it crosses the first sensor and the chronograph starts recording time, the chronograph stops recording time once the bullet crosses the back sensor. Since the distance is fixed between the two sensors on the chronograph, the chronograph calculates the velocity by using: $v = d/t$. Where d is the distance between the sensors, and t is the time it takes for the bullet to cross the two sensors.

The total recorded velocities are given in Table 3, and average velocities are shown in Figure 9. Kinetic energy imparted by the bullets onto the steel plates was calculated using the average velocities: $KE = \frac{1}{2} mv^2$. Results are given in Table 4 and Figure 10.

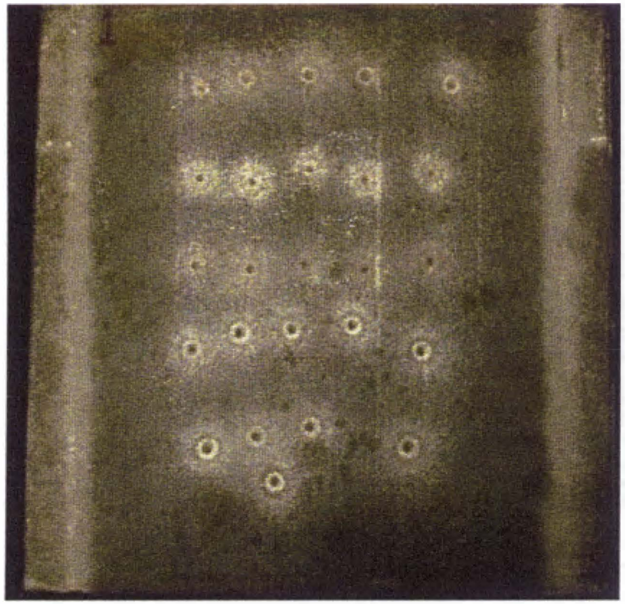


Plate 1

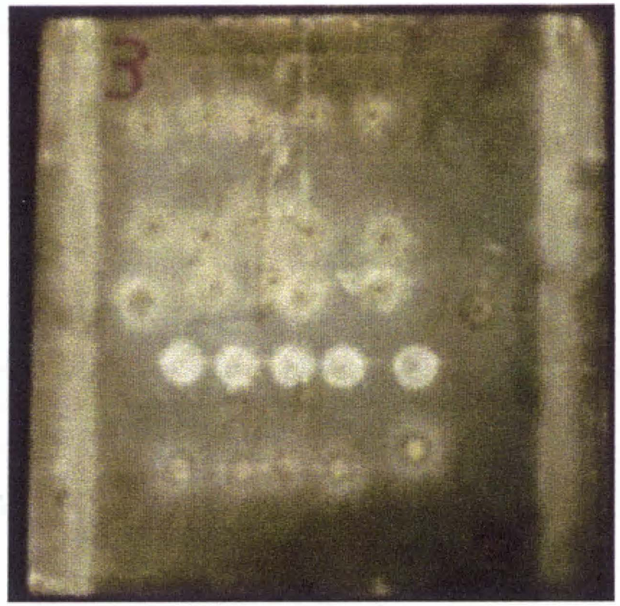


Plate 3

Figure 4. Impact Crater Pictures

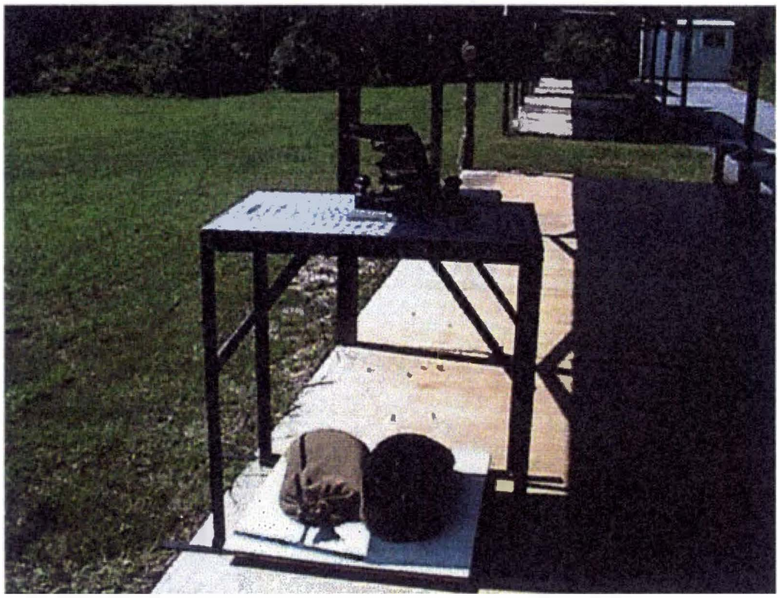


Figure 5. Testing Gun Setup

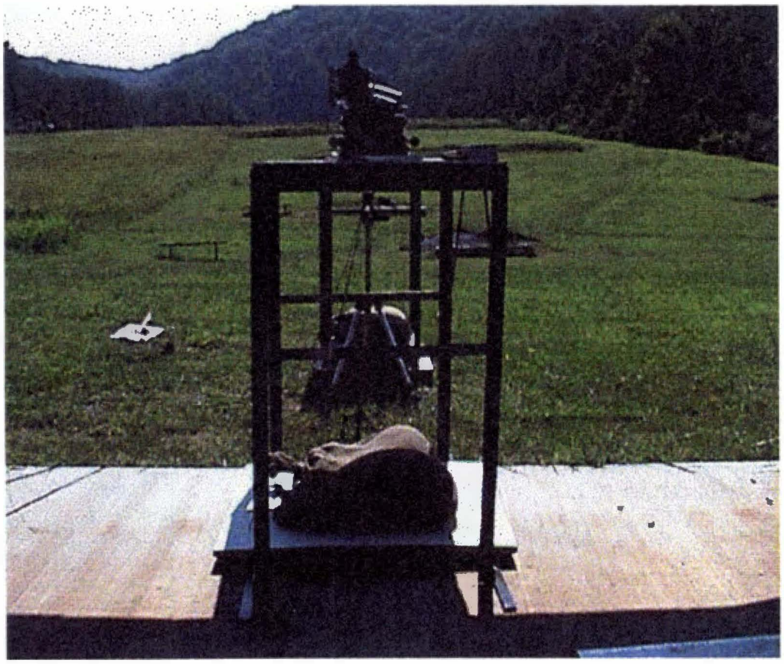


Figure 6. Behind Test Setup

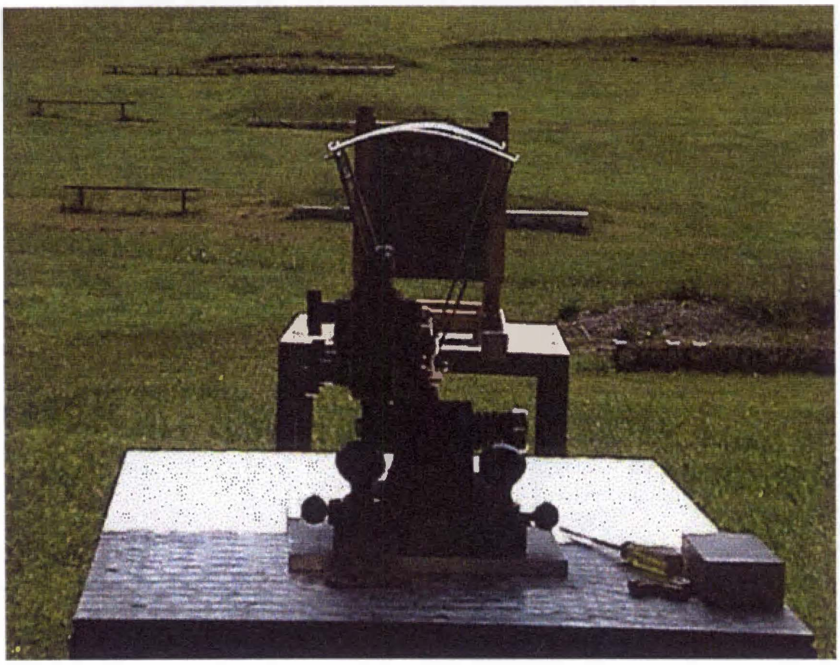


Figure 7. Gun, test plate, and chronometer

Figure 8. Test plate set-up and chronometer

Table 3. **Steel Plate Bullet Velocities**

Plate	Bullet Type	Bullet Weight (grains)	Velocity 1 (fps)	Velocity 2 (fps)	Velocity 3 (fps)	Velocity 4 (fps)	Velocity 5 (fps)	Velocity 6 (fps)	Averag e (fps)
Vary Energy (Mass)									
2	WSn[1] 0100	86.01	945.1	1011.5	916.6	889.3	933.5		939.2
2	WSn 2575	99.46	1007.2	939.0	971.1	987.8	930.6		967.1
2	WSn 3961	111.04	964.2	934.4	931.0	922.7	927.3		935.9
2	WSn 5248	124.00	1004.4	986.0	1005.9	958.1	980.9		987.1
2	WSn 5941	132.53	992.3	677.4[2]	682.1[2]	651.2[2]	979.1	1094.5	846.1
Vary Velocity									
1	(WSn 5248)[3] 3.5 gn 231	124.00	889.5	909.5	864.0	899.8	844.3		881.4
1	4.0 gn 231	124.00	988.4	951.9	975.1	967.5	970.6		970.7
1	4.5 gn 231	124.00	1070.2	1089.3	1059.7	1043.0	1060.2		1064.5
1	5.0 gn 231	124.00	1119.5	1101.3	1100.1	1111.4	1092.2		1104.9
Different Binders									
3	WSn 5248 Fine Sn	124.00	1163.0	1155.9	1131.9	1154.2	1155.1		1152.0
3	WSn 5248 Standard	124.00	1720.1	2664.9	1025.5	951.2	928.3		1458.0
3	WSn 5248 Sn Tailings	124.00	995.0	968.3	963.6	977.8	917.2		964.4
Commercial Frangible Ammunition									
4	Simunition	85.00	1410.1	1382.9	1398.1	1385.0	1392.8		1393.8
4	Delta/Winchester Ranger	83.00	1381.0	NR[4]	1350.0	1387.4	1335.6		1363.5
Lead Rounds									
5	Swaged Pb	125.00	1071.5	1034.1	1047.5	1051.2	1110.2		1062.9
5	Hard Cast Pb	125.00	1049.7	1054.9	1036.3	1033.6	1038.2		1042.5
Other									
3	Winchester-Lead Free Sn Core FMJ	100.00	1137.8	1106.7	1092.4	1113.6	1105.0		1111.1
4	Winchester FMJ Pb	115.00	1069.2	1085.9	1103.1	1094.5	1099.5		1090.4
1	WSn 5941 ¾" Jacket	124.00	1065.7	1057.6	1060.4	1055.5	1056.5		1059.1
3	WSn 5941 FMJ	124.00	1147.9	1092.0	1094.5	1077.2	1172.8		1116.9

1 WSn = Tungsten / Tin Mix
2 Problems with chronograph. Estimated average velocity was calculated at 1022.0 fps from shots 1,5,6.
3 All Bullets in the Vary Velocity group are WSn 5248 with different propellant charge
4 No recorded velocity from chronograph.

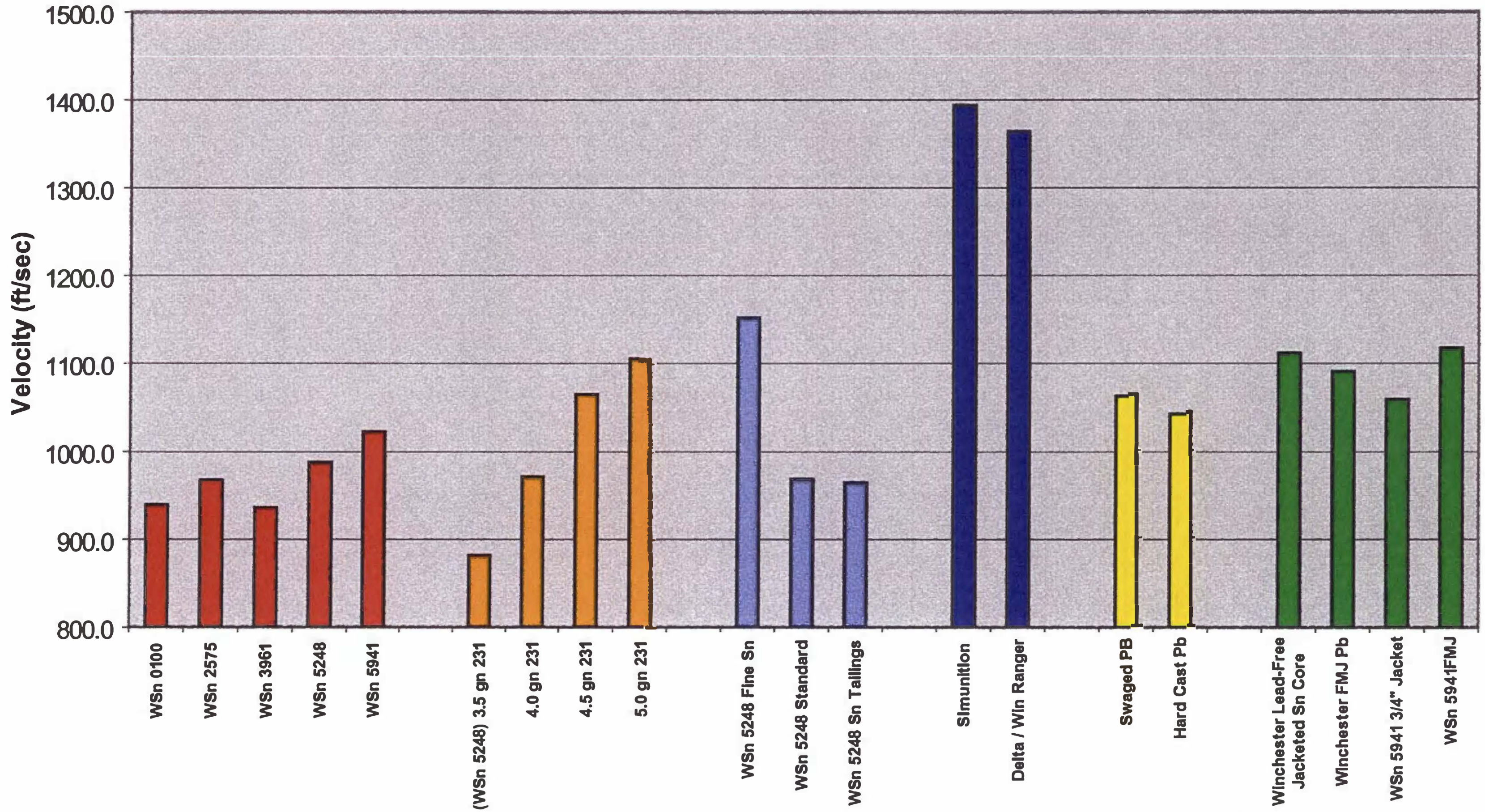


Figure 9. Steel Plate Average Velocities (5 shots per average)

Table 4. **Steel Plate Kinetic Energy**

Plate	Bullet Type	Bullet Mass (grains)	Conversion grain to gram	Conversion gram to kg	Bullet Mass (lb_m)	Avg. Velocity (ft/sec)	Gravity Constant $\frac{(lb_m - ft)}{(lb_f - s^2)}$	KE ($ft\text{-}lb_f$)
Vary Energy (Mass)								
2	WSn 0100	86.01	5.585065	0.005585	0.012313	939.2	32.2	168.651
2	WSn 2575	99.46	6.458442	0.006458	0.014238	967.1	32.2	206.783
2	WSn 3961	111.04	7.210390	0.007210	0.015896	935.9	32.2	216.203
2	WSn 5248	124.00	8.051948	0.008052	0.017751	987.1	32.2	268.576
2	WSn 5941	132.53	8.605844	0.008606	0.018972	1022.0	32.2	307.708
Vary Velocity								
1	(WSn 5248) 3.5 gn 231	124.00	8.051948	0.008052	0.017751	881.4	32.2	214.137
1	4.0 gn 231	124.00	8.051948	0.008052	0.017751	970.7	32.2	259.726
1	4.5 gn 231	124.00	8.051948	0.008052	0.017751	1064.5	32.2	312.346
1	5.0 gn 231	124.00	8.051948	0.008052	0.017751	1104.9	32.2	336.504
Different Binders								
3	WSn 5248 Fine Sn	124.00	8.051948	0.008052	0.017751	1152.0	32.2	365.805
3	WSn 5248 Standard	124.00	8.051948	0.008052	0.017751	968.3	32.2	258.443
3	WSn 5248 Sn Tailings	124.00	8.051948	0.008052	0.017751	694.4	32.2	256.365
Commercial Frangible Ammunition								
4	Simunition	85.00	5.519481	0.005519	0.012168	1393.8	32.2	367.065
4	Delta/Winchester Ranger	83.00	5.389610	0.005390	0.011882	1363.5	32.2	343.014
Lead Rounds								
5	Swaged Pb	125.00	8.051948	0.008052	0.017751	1062.9	32.2	311.408
5	Hard Cast Pb	125.00	8.116883	0.008117	0.017894	1042.5	32.2	301.985
Other								
3	Winchester-Lead Free Sn Core FMJ	100.00	6.493506	0.006494	0.014316	1111.1	32.2	274.429
4	Winchester FMJ Pb	115.00	7.467532	0.007468	0.016463	1090.4	32.2	303.943
1	WSn 5941 ¾" Jacket	124.00	8.051948	0.008052	0.017751	1059.1	32.2	309.185
3	WSn 5941 FMJ	124.00	8.051948	0.008052	0.017751	1116.9	32.2	343.854

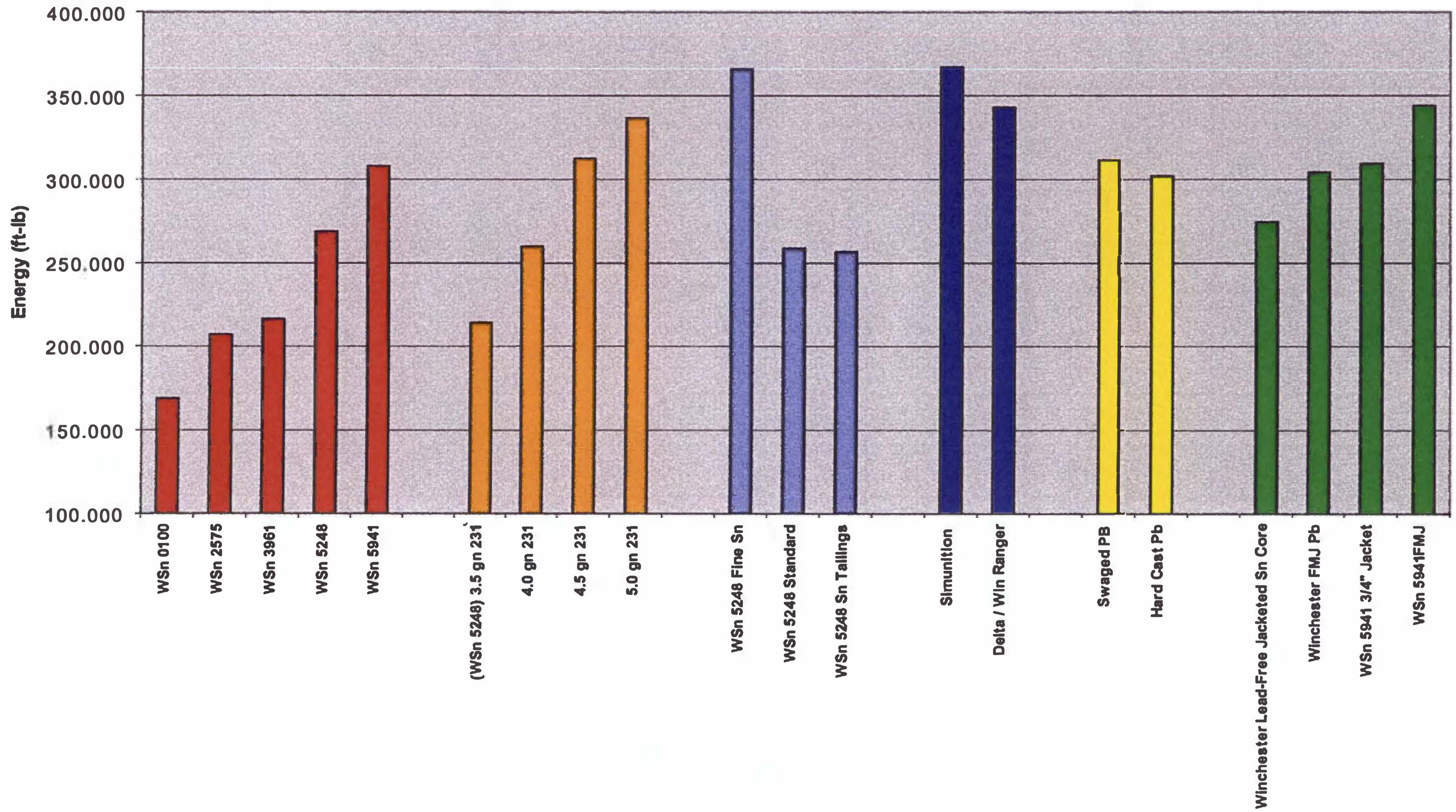


Figure 10. Steel Plate Kinetic Energy

Part 2. Profilometer Measurement

The damage to the surface of the plate, i.e. impact craters, was characterized employing a non-contact laser profilometer. The profilometer provided detailed information about the depth of penetration and cross sectional area.

After shooting the steel plates, they were taken back to ORNL and examined using a Rodenstock RM600 2-D/3-D non-contact profilometer. The plates were placed on the profilometer and analyzed for cross-sectional area and depth of penetration. Some shots were not analyzed due to size constraints of the profilometer table.

The Rodenstock RM600 scans surface structures between 0.02 and 600 microns. During a measurement the steel plate is aligned on the traverse table so that the measuring surface is parallel to the movement direction of the traverse table. Then the sensor is adjusted manually until it is perpendicular to the measuring surface. The optical distance sensor works with an infrared laser whose beam is focused on the surface of the steel plate. A light spot with a diameter of 2 microns is formed on the steel plate surface. The light spot is imaged onto a focus detector in the sensor. When the distance to the measuring surface changes, the detector sends a control signal for the automatic focusing guide. A moving coil system then moves the lens until the laser beam is again focused exactly on the sample surface. The measuring values form a contour profile, which are measured and outputted in graphic form by the computer.

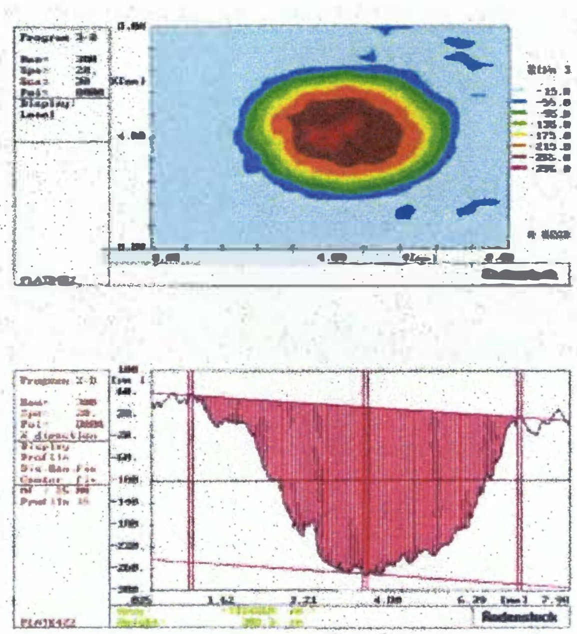
When the steel plate was positioned as described above and the sensor was at the correct measuring distance at the beginning of the measuring path, parameters were entered to get a detailed analysis of the shots. The following parameters were used in this study:

- Range: Measuring range of the sensor. 300µm.
- Length: The length of the measurement path in both X and Y values. 8mm.
- Speed: Sets the movement speed; smaller values for higher measuring precision. 20 mm/min.
- Points: Total number of measuring points; higher values increase the measuring precision, smaller values reduce computation time and the memory requirements on the disk. 8000.

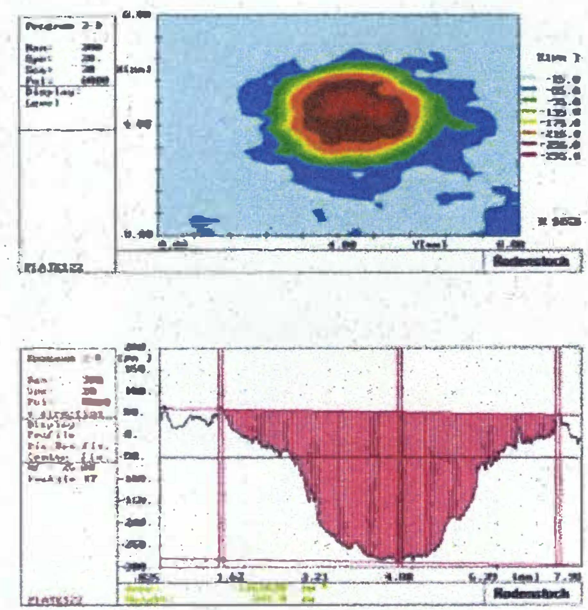
A summary of the profilometer data is given in Table 5, and Figures 11–14. Examples of profilometer printouts are given in Figures 15 and 16. Bullet pictures for the steel plate impact test are given in Figures 17–27.

TEST METHODS GELATIN PREPARATION AND BULLET FRAGMENT ANALYSIS

The second procedure that was employed to determine frangibility, involved looking at the fragments generated upon impact. This was accomplished by firing the bullets against a hardened steel plate (AR400 steel) at a distance of 10 ft, with a gelatin donut ring attached to the plate. The plate's hardened surface minimized damage done by the bullets. The particles generated upon impact were captured by firing through the hole in the center of the block of 10% ballistic gelatin, which was clamped against the hardened steel plate. This technique was inspired by interaction with the FBI at Quantico. The angle of dispersion from the surface, and the size and energy of the particles were examined using this method. These factors were then used to help assess the "frangibility" of a given bullet against selected targets.

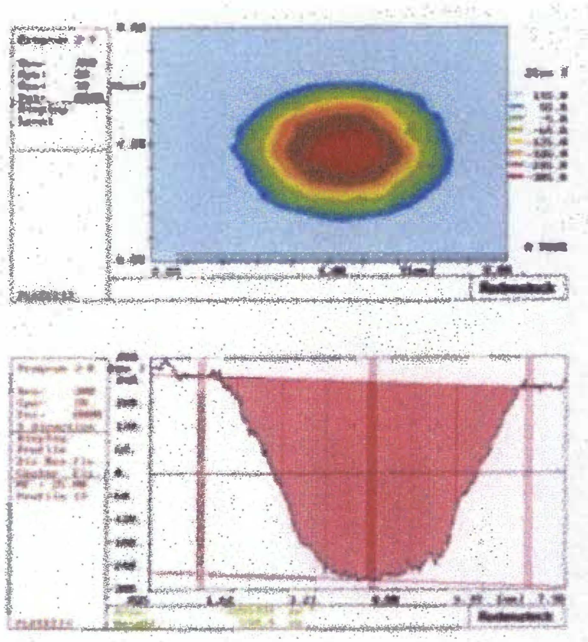


Simunition Shot 2

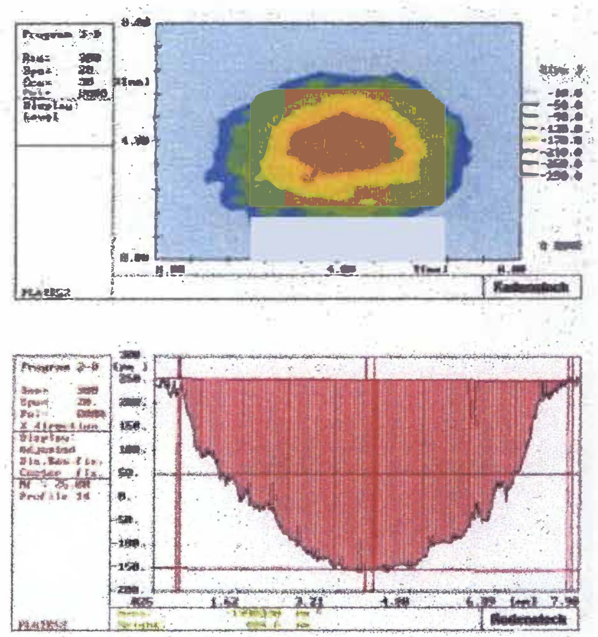


(WSn 5248) 3.5 gn 231 Shot 2

Figure 11. Example Profilometer Output



WSn 5941 ¾" Jacket Shot 3



Swaged Pb Shot 1

Figure 12. Example Profilometer Output

Table 5. **Profilometer Impact Analysis**

Plate	Bullet Type	Wt. (Grains)	Shot #1 Depth (µm)	Area (X 10^6 µm^2)	Shot #2 Depth (µm)	Area (X 10^6 µm^2)	Shot #3 Depth (µm)	Area (X 10^6 µm^2)	Shot #4 Depth (µm)	Area (X 10^6 µm^2)	Shot #5 Depth (µm)	Area (X 10^6 µm^2)
Vary Energy (Mass)												
2	WSn 0100	86.01	178.1	0.53	165.0	0.40	151.1	0.39	175.0	0.33	NR	NR
2	WSn 2575	99.46	239.0	0.72	194.7	0.55	165.4	0.52	249.3	0.71	202.3	0.50
2	WSn 3961	111.04	247.8	0.96	209.2	0.69	167.2	0.62	204.7	0.78	231.3	0.70
2	WSn 5248	124.00	350.7	1.12	312.9	1.04	287.4	0.88	330.0	1.21	291.3	0.82
2	WSn 5941	132.00	391.2	1.31	295.4	0.96	319.5	1.21	349.7	1.16	303.7	0.98
Vary Velocity												
1	(WSn 5248) 3.5 gn 231	124.00	237.3	0.67	341.8	1.16	310.7	1.10	316.1	0.98	220.2	0.57
1	4.0 gn 231	124.00	339.3	1.08	301.4	0.98	336.7	1.18	324.7	0.94	323.7	1.10
1	4.5 gn 231	124.00	468.7	1.82	419.4	1.56	513.6	2.16	501.2	1.97	494.6	2.00
1	5.0 gn 231	124.00	506.5	2.08	489.9	1.81	1541.8	2.39	530.9	2.26	537.4	2.27
Different Binders												
3	Fine Sn	124.00	365.3	1.15	358.1	1.19	423.3	1.44	471.2	1.72	344.3	1.21
3	Standard	124.00	312.3	0.95	298.6	0.85	365.2	1.23	289.9	1.23	273.8	0.72
3	Tailings	124.00	310.4	0.93	221.1	0.52	212.1	0.57	178.2	0.39	216.0	0.70
Commercially Frangible Ammunition												
4	Simunition	85.00	319.7	1.21	303.3	1.11	272.1	0.96	302.5	1.19	318.1	1.17
4	Delta/Win Ranger	83.00	274.9	0.95	327.0	1.26	270.9	1.05	268.2	0.98	291.3	1.04
Lead Rounds												
5	Swaged Pb	125.00	404.6	2.00	293.3	0.98	320.2	1.09	361.6	1.82	352.2	1.43
5	Hard Cast Pb	125.00	285.9	0.94	303.5	0.97	36.1	1.10	292.8	0.89	283.8	0.93
Other												
3	Win Lead-Free Jacketed Sn Core	100.00	296.2	1.22	309.1	1.38	300.1	1.33	278.4	1.18	268.3	1.21
4	Win FMJ Pb	115.00	220.8	0.70	231.9	0.74	266.4	0.95	237.0	0.88	208.3	0.77
1	5941 ¾" Jacket	124.00	444.1	1.79	524.6	1.86	510.4	1.90	426.0	1.46	NR	NR
3	5941 FMJ[2]	124.00	414.3	1.03	143.8	0.33	135.1	0.25	225.2	0.56	216.1	0.52

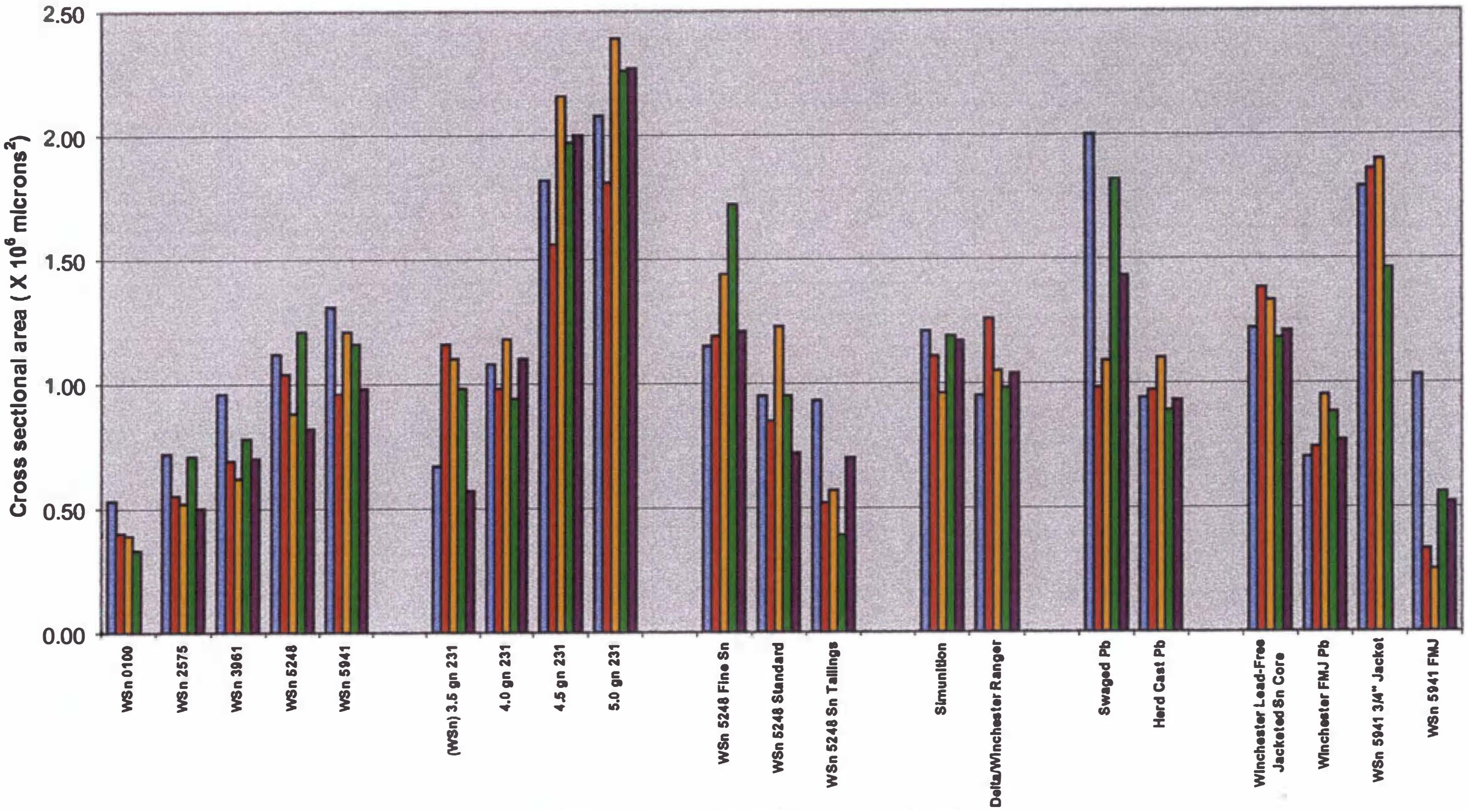


Figure 13. Profilometer Area

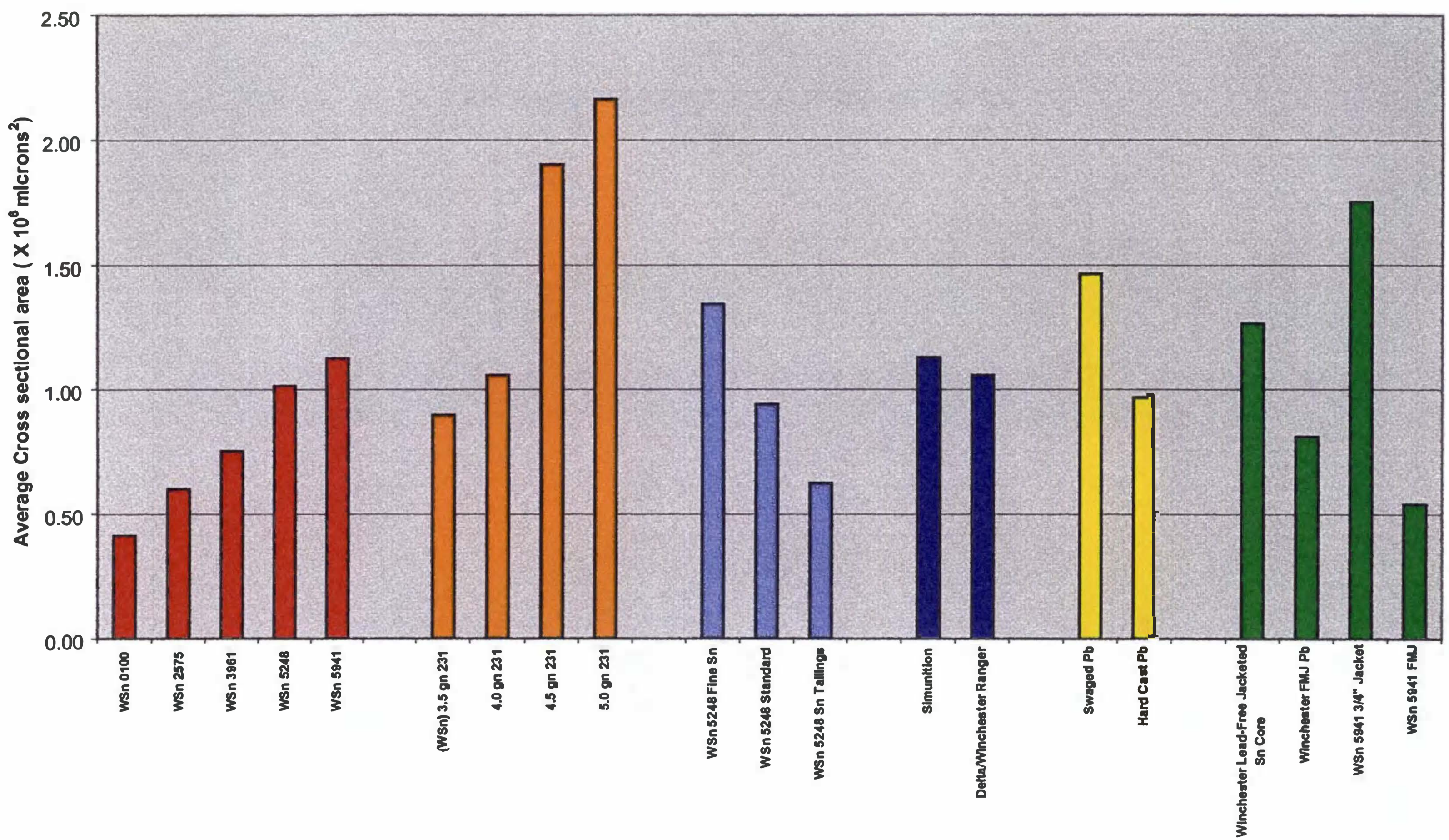


Figure 14. Average Profilometer Area

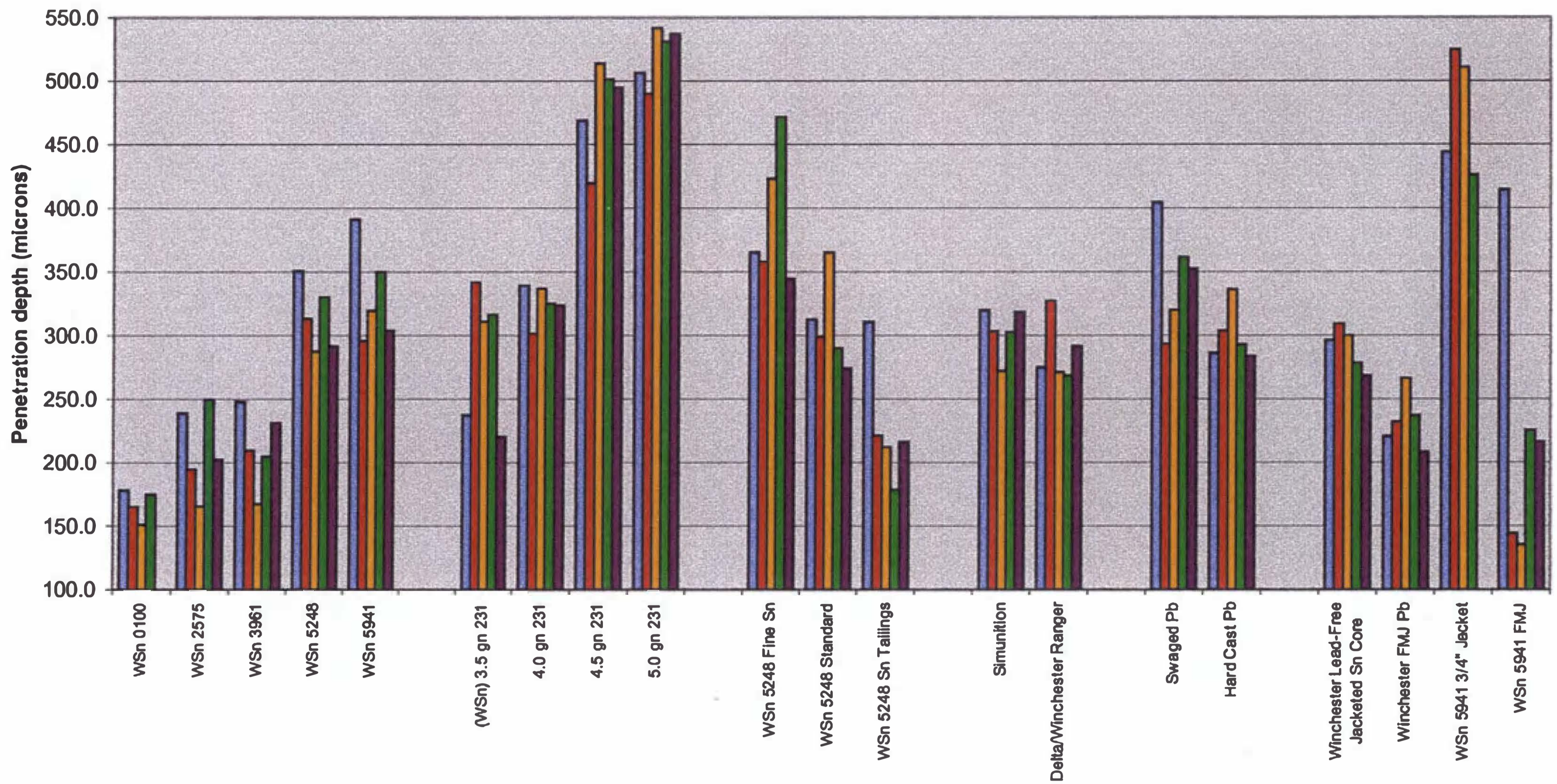


Figure 15. Profilometer Penetration Depth

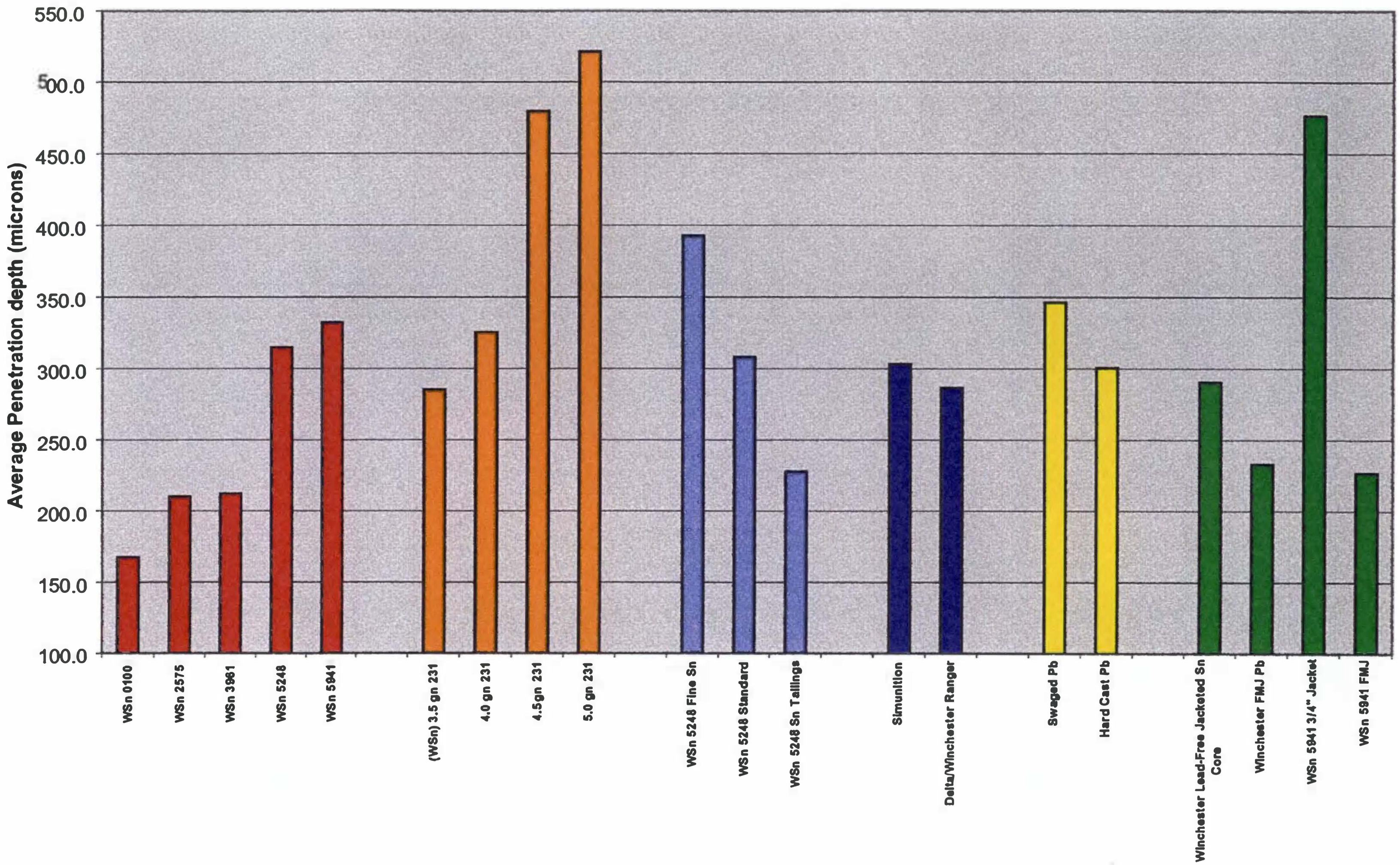
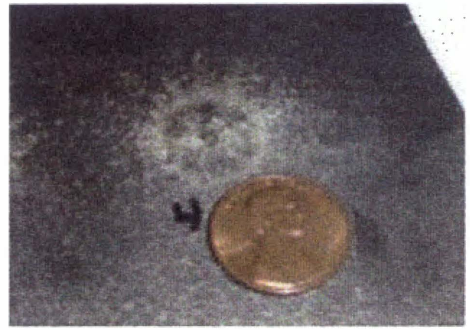


Figure 16. Profilometer Average Penetration Depth

Vary Energy

WSn 0100 Shot 1 & 2

WSn 0100 Shot 3 & 5



WSn 0100 Shot 4

Vary Energy

WSn 2575 Shot 1 & 2

WSn 2575 Shot 3 & 4

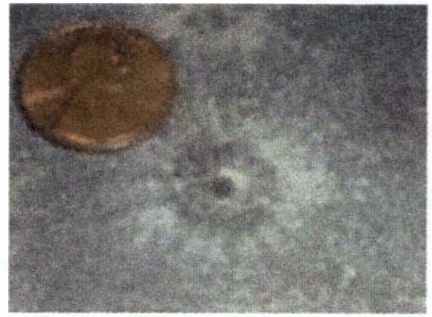
WSn 2575 Shot 5

Figure 17. Impact Crater Pictures WSn 0100 & WSn 2575

Vary Energy

WSn 3961 Shot 1 & 2

WSn 3961 Shot 3 & 4



WSn 3961 Shot 5

Vary Energy

WSn 5248 Shot 1

WSn 5248 Shot 3 & 4

WSn 5248 Shot 5 & 6

Figure 18. Impact Crater Pictures WSn 3961 & WSn 5258

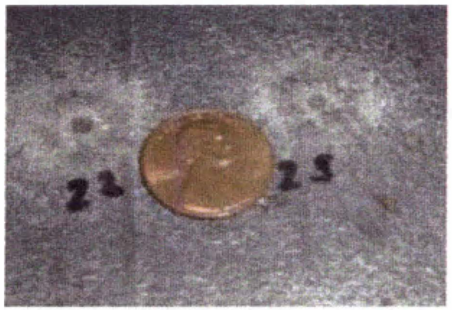
Vary Energy (Mass)

WSn 5941 Shot 1 & 2

WSn 5941 Shot 3 & 4

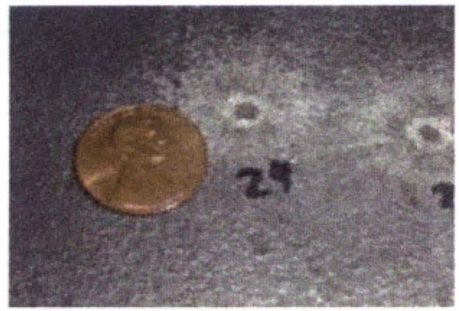
WSn 5941 Shot 4

Vary Velocity



3.5 gn 231 Shot 2 & 5

3.5 gn 231 Shot 1 & 3

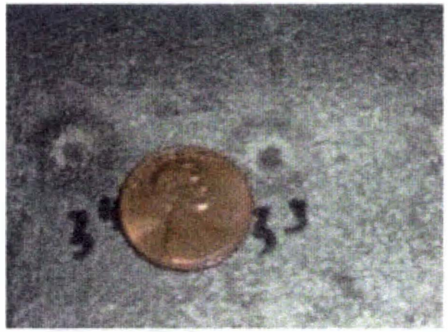


3.5 gn 231 Shot 4

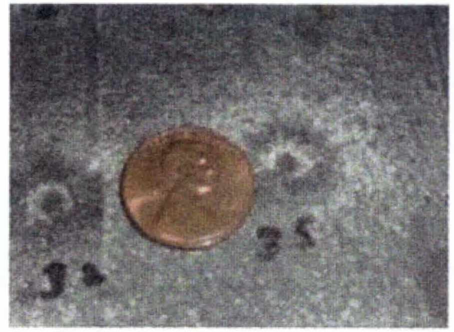
Figure 19. Impact Crater Pictures WSn 5961 & 3.5 gn 231

Vary Velocity

4.0 gn 231 Shot 1 & 2

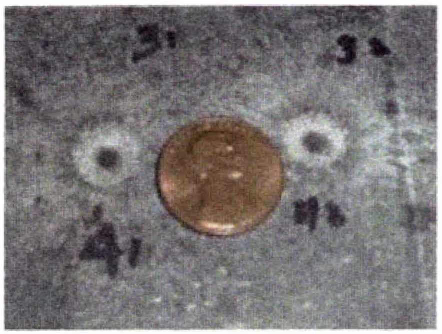


4.0 gn 231 Shot 3 & 4

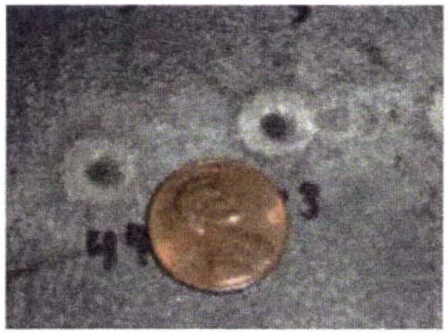


4.0 gn 231 Shot 5 & 2

Vary Velocity



4.5 gn 231 Shot 1 & 2



4.5 gn 231 Shot 3 & 4

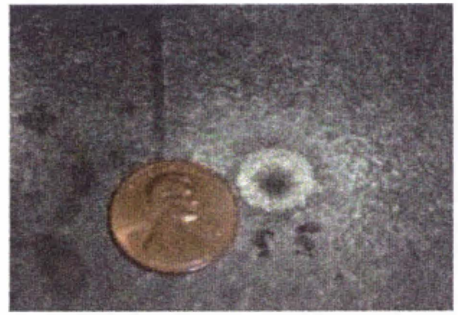
4.5 gn 231 Shot 5

Figure 20. Impact Crater Pictures 4.0 gn 231 & 4.5 gn 231

Vary Velocity

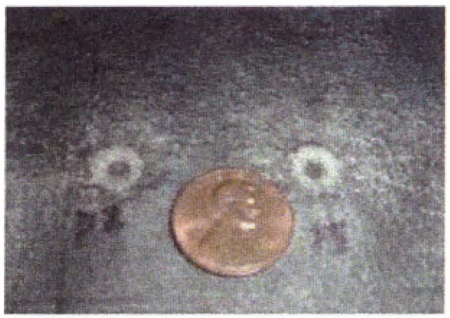
5.0 gn 231 Shot 1

5.0 gn 231 Shot 2 & 3 & 4

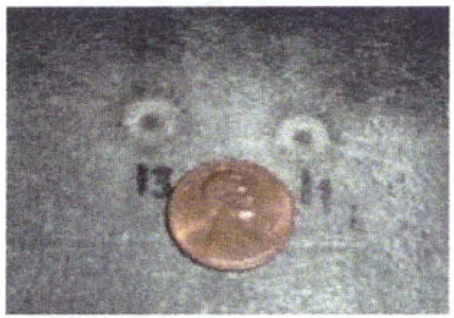


5.0 gn 231 Shot 5

Different Binders



WSn 5248 Fine Sn Shot 2 & 5



WSn 5248 Fine Sn Shot 1 & 3

WSn 5248 Fine Sn Shot 4 & 3

Figure 21. Impact Crater Pictures 5.0 gn 231 & WSn 5248 Fine Sn

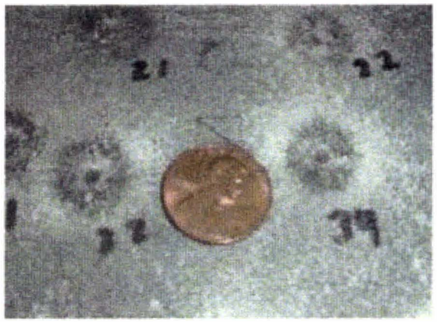
Different Binders

WSn 5248 Standard Shot 1 & 3

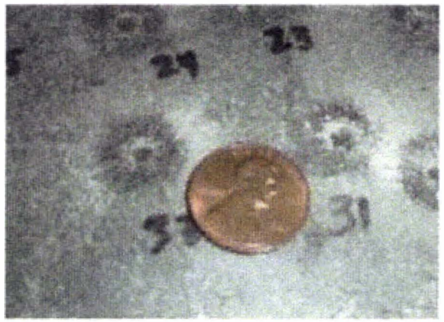
WSn 5248 Standard Shot 1 & 2

WSn 5248 Standard Shot 4 & 5

Different Binders



WSn 5248 Sn Tailings Shot 2 & 4



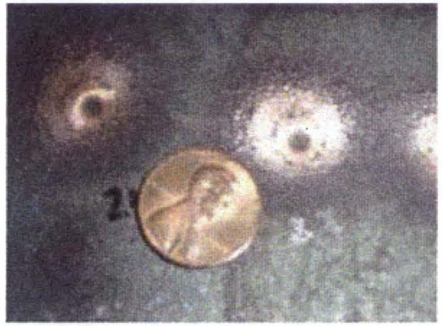
WSn 5248 Sn Tailings Shot 1 & 3

WSn 5248 Sn Tailings Shot 5

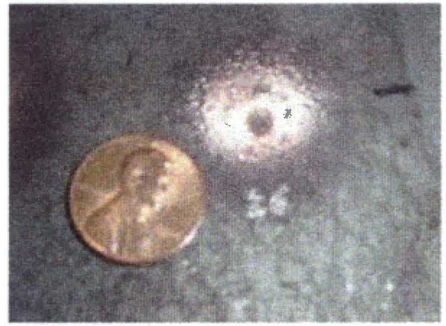
Figure 22. Impact Crater Pictures WSn 5248 Standard & Sn Tailings

Commercially Frangible Ammunition

Simunition Shot 3 & 1



Simunition Shot 4 & 2



Simunition Shot 5

Commercially Frangible Ammunition

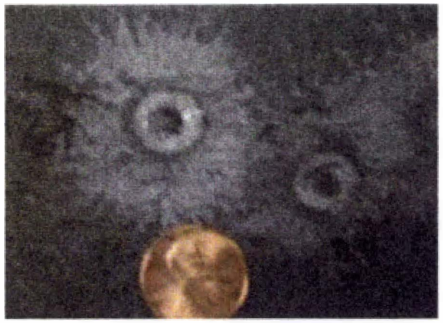
Delta/Winchester Ranger Shot 2

Delta/Winchester Ranger Shot 3

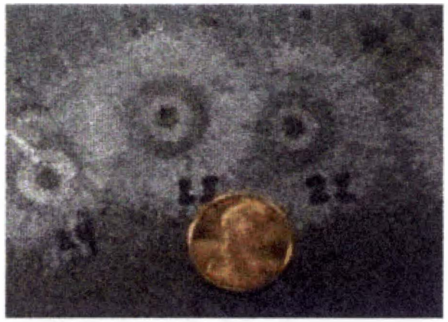
Delta/Winchester Ranger Shot 4

Figure 23. Impact Crater Pictures Simunition & Delta/Winchester Ranger

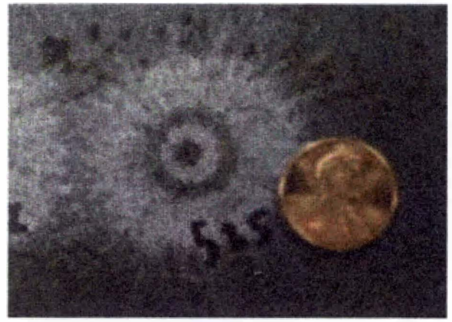
Lead Rounds



Swaged Pb Shot 1 & 4

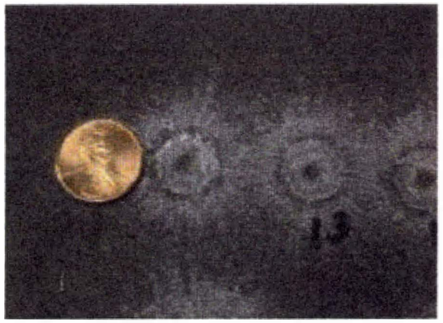


Swaged Pb Shot 4 & 3 & 2

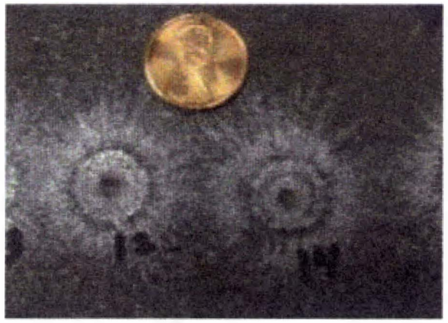


Swaged Pb Shot 5

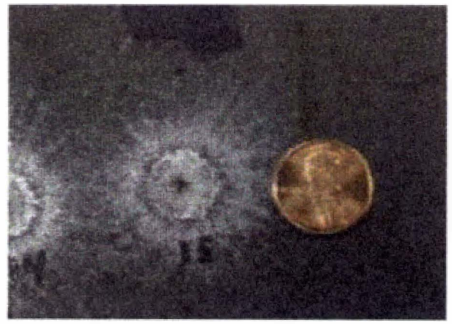
Lead Rounds



Hard Cast Pb Shot 1 & 3



Hard Cast Pb Shot 2 & 4



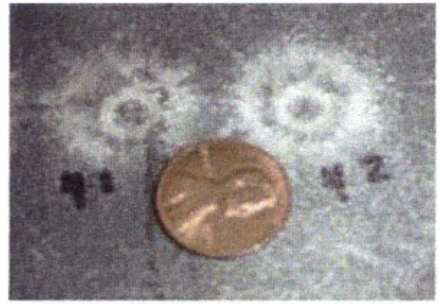
Hard Cast Pb Shot 5

Figure 24. Impact Crater Pictures Swaged Pb & Hard Cast Pb

Other

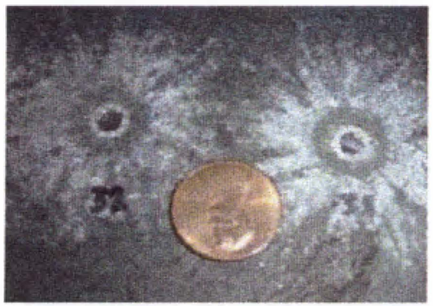
Winchester Lead-Free Jacketed Sn Core Shot 3

Winchester Lead-Free Jacketed Sn Core Shot 5 & 4

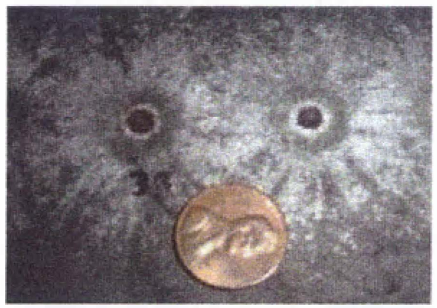


Winchester Lead-Free Jacketed Sn Core Shot 1 & 2

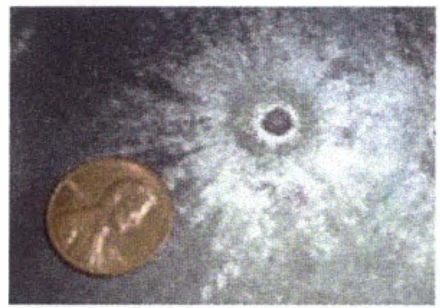
Other



Winchester FMJ Pb Shot 2 & 5



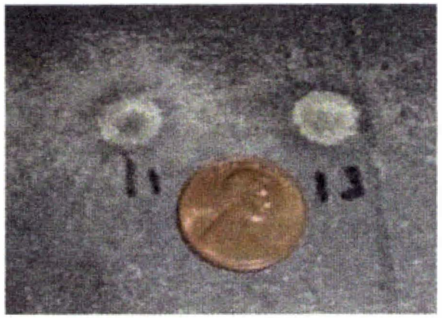
Winchester FMJ Pb Shot 3 & 1



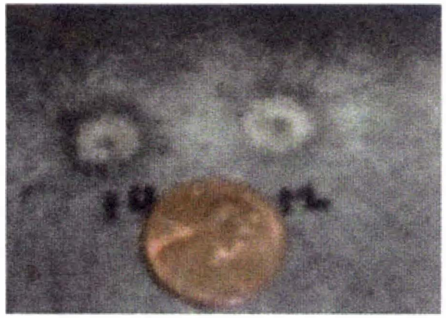
Winchester FMJ Pb Shot 4

Figure 25. Impact Crater Pictures Winchester Sn Core & FMJ

Other



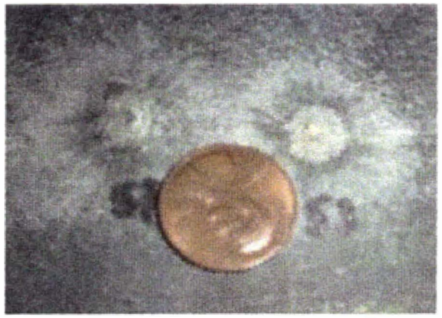
WSn 5941 ¾" Jacket Shot 1 & 3



WSn 5941 ¾" Jacket Shot 4 & 2

WSn 5941 ¾" Jacket Shot 5

Other



WSn 5941 FMJ Shot 1 & 3

WSn 5941 FMJ Shot 4

WSn 5941 FMJ Shot 5 & 2

Figure 26. Impact Crater Pictures WSn 5941 ¾" Jacket & FMJ

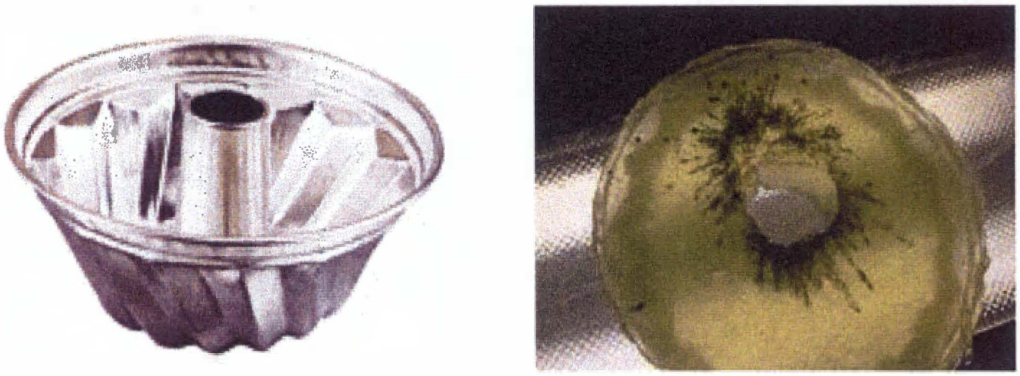


Figure 27. Gelatin Mold and Capture Gelatin

To analyze the particles generated upon impact with a frangible bullet, gelatin donut rings were employed to capture fragments after impacting the AR400 hardened steel plate. Gelatin donut rings were created from Savarin™ non-stick angel food cake molds, as shown in Figure 27.

Ballistic gelatin used in this study was obtained from the Kind and Knox Division of Knox Gelatin. There are different methods on how to prepare ballistic gelatin.[42] During the course of this study, all ballistic gelatin was prepared in the manner described below.

- 9 L of water was measured and poured into a steel pot.
- A Corning hot plate was used to heat up the water to 135°F.
- A Beckman 600 series thermocouple was used to monitor water temperature.
- 4 drops of cinnamon oil were added to the water to retard foaming while mixing.
- A CAFRAMO variable speed mixer was used to stir the water for heating.

- 6 ml of Propionic acid were added to inhibit fungi growth. (Pure stock solution obtained from JT Baker Analyzed #V-330-07 obtained from V.W.R. Scientific, Seattle, WA).
- 1kg (2.205 lb.) of Kind & Knox, Type 250-A Ordnance Gelatin was measured.
- Powder was slowly poured into the stirring water. (It takes roughly 60 seconds to pour the powdered gelatin into the hot water to ensure it mixes thoroughly).
- After adding powder, temperature was kept at 125°F, and mixed for 15 minutes. That ensured that all powder was dissolved and mixed properly.
- The stirrer was turned off and removed, and the hot plate was turned off. A scoop was used to skim off the foam that rose to the top of the mixture.
- The mixture was slowly poured into the mold pan, covered, and left at room temperature for 24 hours.
- The mold pan was placed in the refrigerator set between 35 and 39°F for 24 hours.
- After 24 hours, the gelatin block was removed from the mold pan. The gelatin block was wrapped in "Saran wrap" to prevent evaporation.

The gelatin blocks were clamped between the AR400 hardened steel plate and a piece of wood with the center cut out. After each bullet type was fired, the armor plate was thoroughly cleaned so as not to contaminate the next shot. A new gelatin block was used for each bullet group. Gelatin blocks were removed and placed in individually labeled bags. Due to time constraints only a handful of bullets were tested and captured as compared to the steel plate test. Pictures of the ballistic gelatin donut rings after being shot are shown in Figure 28.

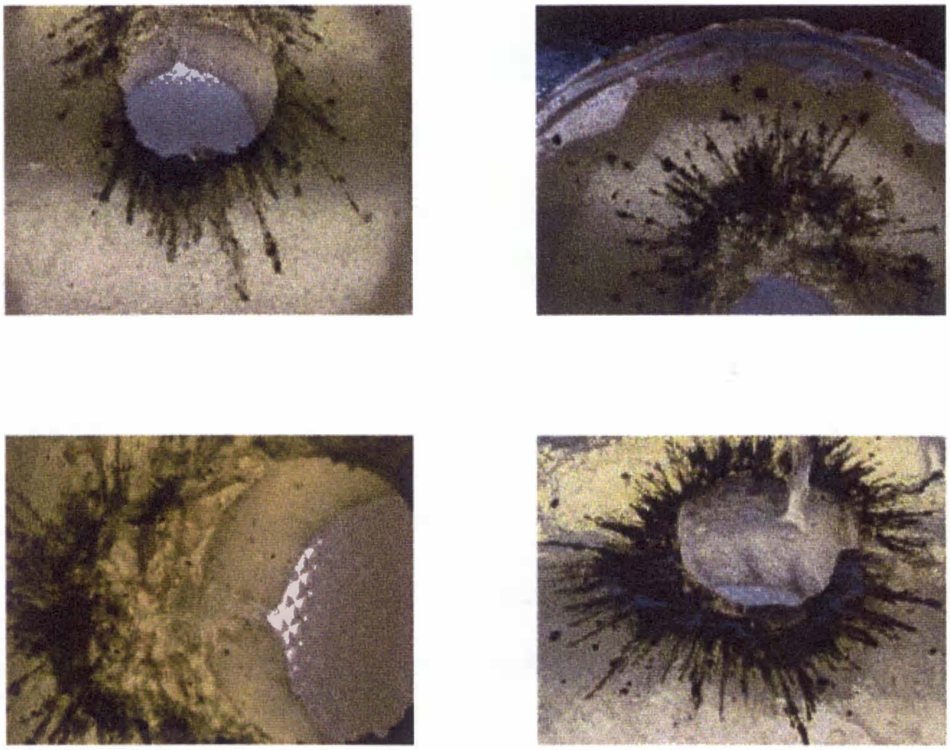


Figure 28. Gelatin Capture Pictures

The blocks were taken back to ORNL , analyzed ,melted down, and the liquid was then poured through a series of four sieves of different mesh sizes to capture bullet fragments. The sieve meshes were as follows:

1. Sieve 1 = 0.0469 in. (>1190 microns)
2. Sieve 2 = 0.0331 in. (1189 – 841 microns)
3. Sieve 3 = 0.0165 in. (840 – 425 microns)
4. Sieve 4 = 0.0117 in. (424 – 297 microns)

Any particles less than 296 microns were considered dust and not enough of a factor to measure. The total capture weight results for the testing are shown in Table 6, and Figure 29 and 30. Figure 31 shows a breakdown graphically for the WSn 5248 bullet.

Table 7 and Figure 32 show the results of the gelatin capture weight %.. Multiplying the number of rounds fired and the Bullet Wt gives you the Max Capture Weight. The % Captured is found by dividing the Sum Captured by the Max Capture Weight. This value was how much was captured in all four sieves. To determine the individual percentage for each sieve, the capture values for each sieve from table 6 were divided by the Sum Captured. The % Dust term represents all the material that either was not captured due to ricochets straight out of the gelatin capture hole, or was so fine and powdery that it went through all four of the sieves after being melted down and was unable to be captured.

After weighing out the fragments captured, a sample of fragments was removed and weighed again. The particles generated in the gelatin capture test were separated by diameter and each size fraction weighed. The sample weight's fragments were counted and a weight per particle for the first three sieves was determined, this information is given in Table 8 and in Figures 33 and 34. This information is important in looking at the amount of energy fragments have after the bullets break up upon impact.

Table 6. Gelatin Capture Weights

Shots	Bullet Type	Bullet Wt. (grains)	Sieve #1 (grains)	Sieve #2 (grains)	Sieve #3 (grains)	Sieve #4 (grains)	Sum (grains)
Vary Energy (Mass)							
3	WSn 0100	86.01	63.728	10.732	25.110	11.210	110.780
3	WSn 2575	99.46	85.373	24.934	29.322	8.792	148.421
3	WSn 3961	111.04	96.410	19.504	27.832	7.477	151.223
4	WSn 5248	124.00	134.387	33.433	52.576	13.455	233.851
3	WSn 5941	132.00	95.327	25.208	39.499	11.002	170.946
Vary Velocity							
3	(WSn 5248) 3.5 gn 231	124.00	91.973	20.810	29.004	7.073	138.860
4	4.0 gn 231	124.00	134.387	33.433	52.576	13.455	233.851
3	4.5 gn 231	124.00	46.054	19.379	32.017	10.726	108.176
2	5.0 gn 231	124.00	16.306	8.097	12.921	4.577	41.900
Different Binders							
3	Fine Sn	124.00	74.655	29.613	47.994	9.797	162.059
4	Standard	124.00	134.387	33.433	52.576	13.455	233.851
4	Sn Tailings	124.00	58.415	20.428	44.069	17.725	140.637
Commercially Frangible Ammunition							
3	Simunition	85.00	73.256	28.940	63.747	17.824	183.767
3	Delta/Winchester Ranger	83.00	110.027	31.829	42.233	8.917	193.005
Lead Rounds							
3	Hard Cast Pb	124.00	201.794	2.955	2.091	.242	207.082

- Total Bullet Wt. that could be Captured = # of shots times Bullet Wt. (grains)
- Sum (grains) (Total captured material) = Sieve #1 + Sieve #2 + Sieve #3 + Sieve #4

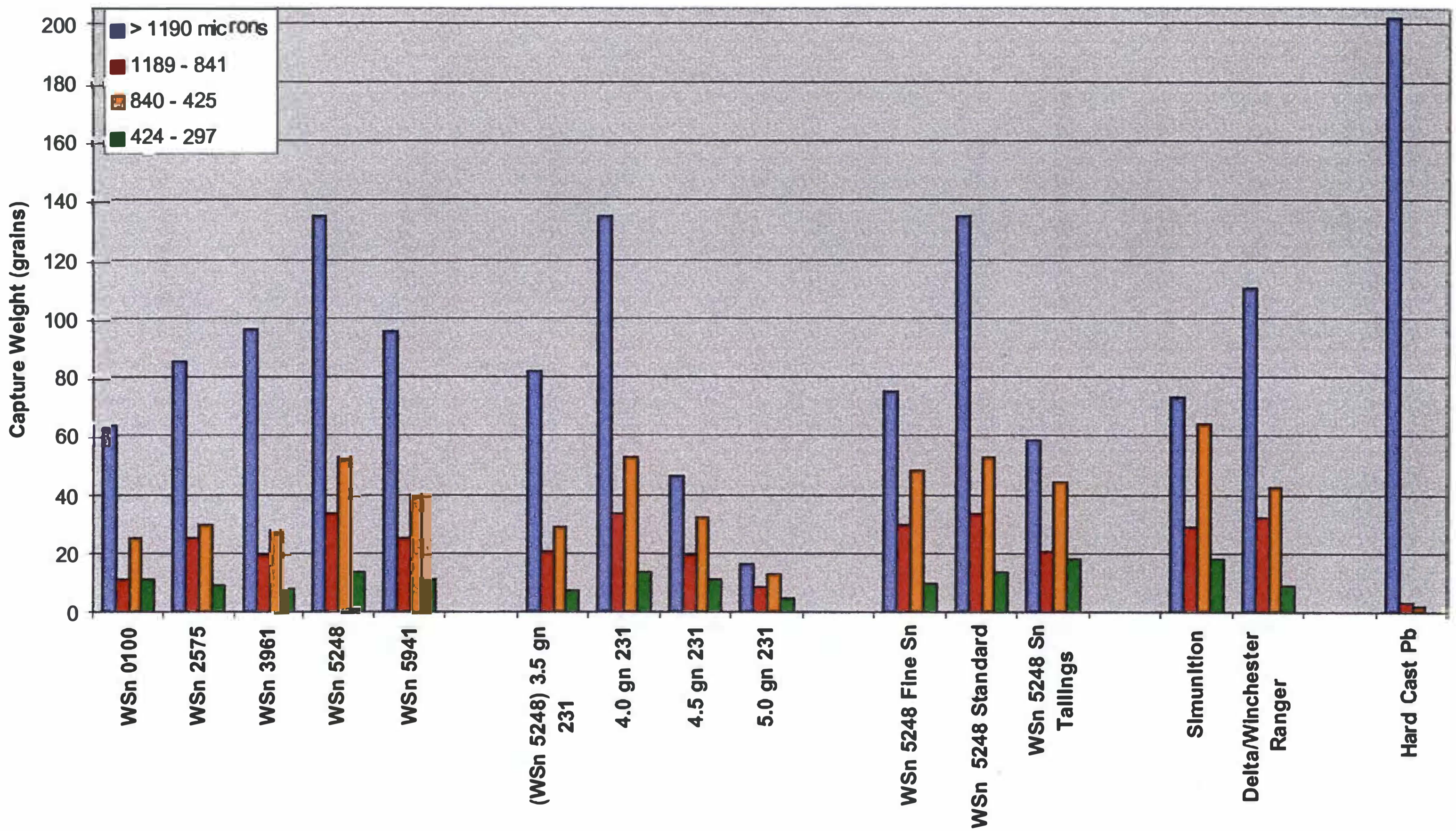


Figure 29. Gelatin Capture Weight

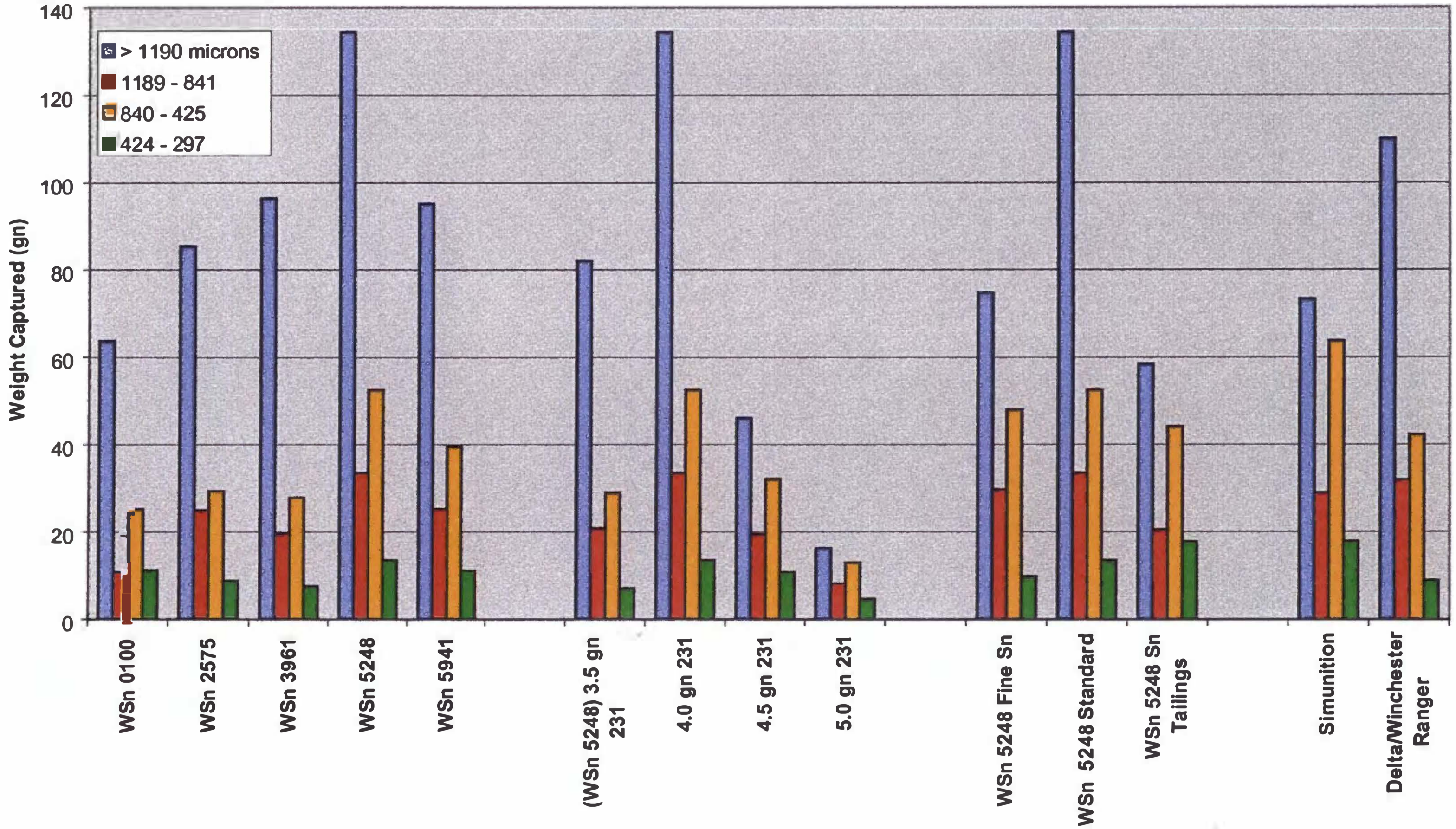


Figure 30. Gelatin Capture Weight (No Pb)

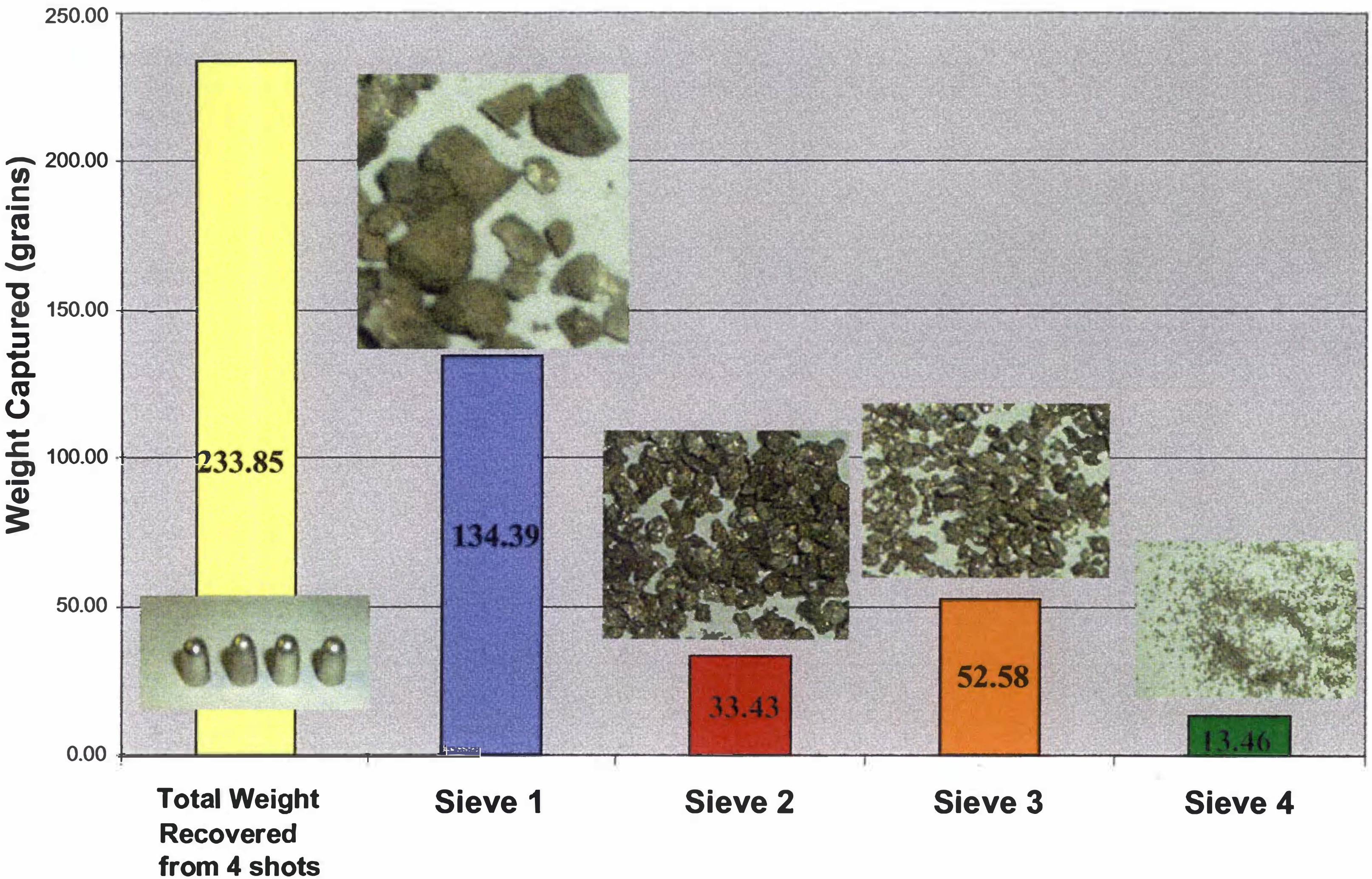


Figure 31. WSn 5248 Example Gelatin Capture Weight

Table 7. **Gelatin Capture Weight %**

Shots	Bullet Type	Bullet Wt. (grains)	Sum Captured (grains)	Total Capture Wt. (grains)	% Captured	% S1	% S2	% S3	% S4	% Dust
Vary Energy (mass)										
3	WSn 0100	86.01	110.780	258.03	42.93	24.70	4.16	9.73	4.34	57.07
3	WSn 2575	99.46	148.421	298.38	49.74	28.61	8.36	9.83	2.95	50.26
3	WSn 3961	111.04	151.223	33.12	45.40	28.94	5.85	8.36	2.24	54.60
4	WSn 5248	124.00	233.851	496.00	47.15	27.09	6.74	10.60	2.71	52.85
3	WSn 5941	132.00	170.946	396.00	43.17	24.05	6.37	9.97	2.78	56.83
Vary Velocity										
3	(WSN 5248) 3.5 gn 231	124.00	138.860	372.00	37.33	22.04	5.59	7.80	1.90	62.87
4	4.0 gn 231	124.00	233.851	496.00	47.15	27.09	6.74	10.60	2.71	52.85
3	4.5 gn 231	124.00	108.176	372.00	29.08	12.38	5.21	8.61	2.88	70.92
2	5.0 gn 231	124.00	41.900	248.00	16.90	6.57	3.27	5.21	1.85	83.10
Different Binders										
3	Fine Sn	124.00	162.059	372.00	43.56	20.07	7.96	12.90	2.63	56.44
4	Standard	124.00	233.851	496.00	47.15	27.09	6.74	10.60	2.71	52.85
4	Sn Tailings	124.00	140.637	496.00	28.35	11.78	4.12	8.88	3.57	71.65
Commercially Frangible Ammunition										
3	Simunition	85.00	183.767	255.00	72.07	28.73	11.35	25.00	6.99	27.93
3	Delta/Winchester Ranger	83.00	193.005	249.00	77.51	44.19	12.78	16.96	3.58	22.49
Lead Rounds										
3	Hard Cast Pb	124.00	207.082	372.00	55.67	54.25	0.79	0.56	0.06	44.33

- S1 = Sieve 1 (> 1190 microns)
- S2 = Sieve 2 (1189 – 841)
- S3 = Sieve 3 (840 – 425)
- S4 = Sieve 4 (424 – 297)
- Dust (< 290 microns)
- Total Capture Wt. (grains) = # of shots times Bullet Wt. (grains)

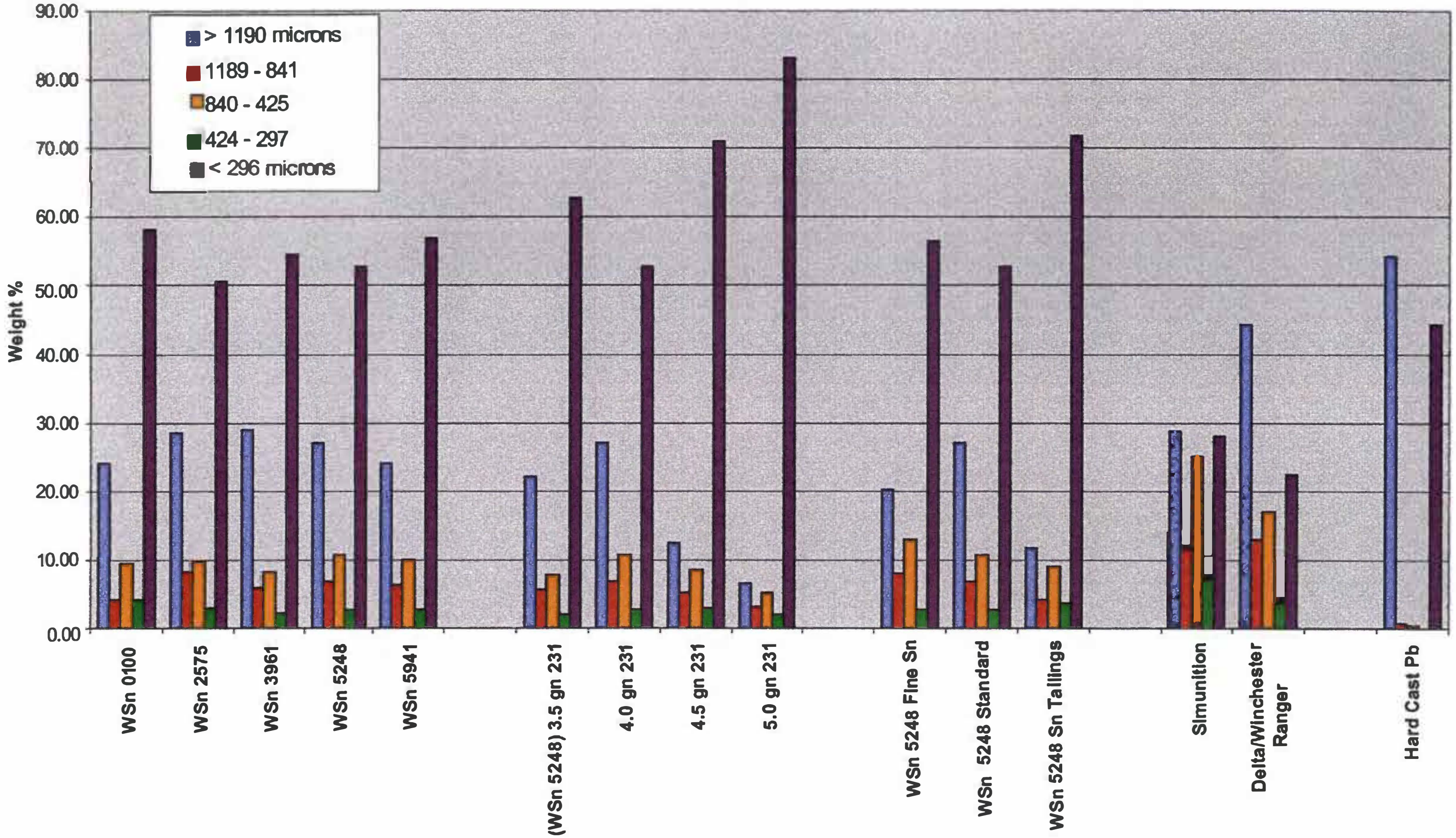


Figure 32. Gelatin Capture Weight %

Table 8. **Weight per Particle**

	Weight/Particle (gn)		
Bullet Type	**> 1190 μm**	**1189 – 841 μm**	**840 – 425 μm**
Vary Energy (mass)			
WSn 0100	.2863	.0421	.0160
WSn 2575	.4756	.0690	.0207
WSn 3961	.6147	.0618	.0182
WSn 5248	.6013	.0973	.0307
WSn 5941	.7087	.1067	.0240
Vary Velocity			
(WSN 5248) 3.5 gn 231	.5005	.0893	.0200
4.0 gn 231	.6013	.0973	.0307
4.5 gn 231	.4829	.0920	.0307
5.0 gn 231	.4713	.0827	.0200
Different Binders			
Fine Sn	.6733	.1187	.0267
Standard	.6013	.0973	.0307
Sn Tailings	.5187	.0707	.0147
Commercially Frangible Ammunition			
Simunition	.4039	.0343	.0080
Delta/Winchester Ranger	.1514	.0305	.0133
Lead Rounds			
Hard Cast Pb	2.8319	.0627	.0347

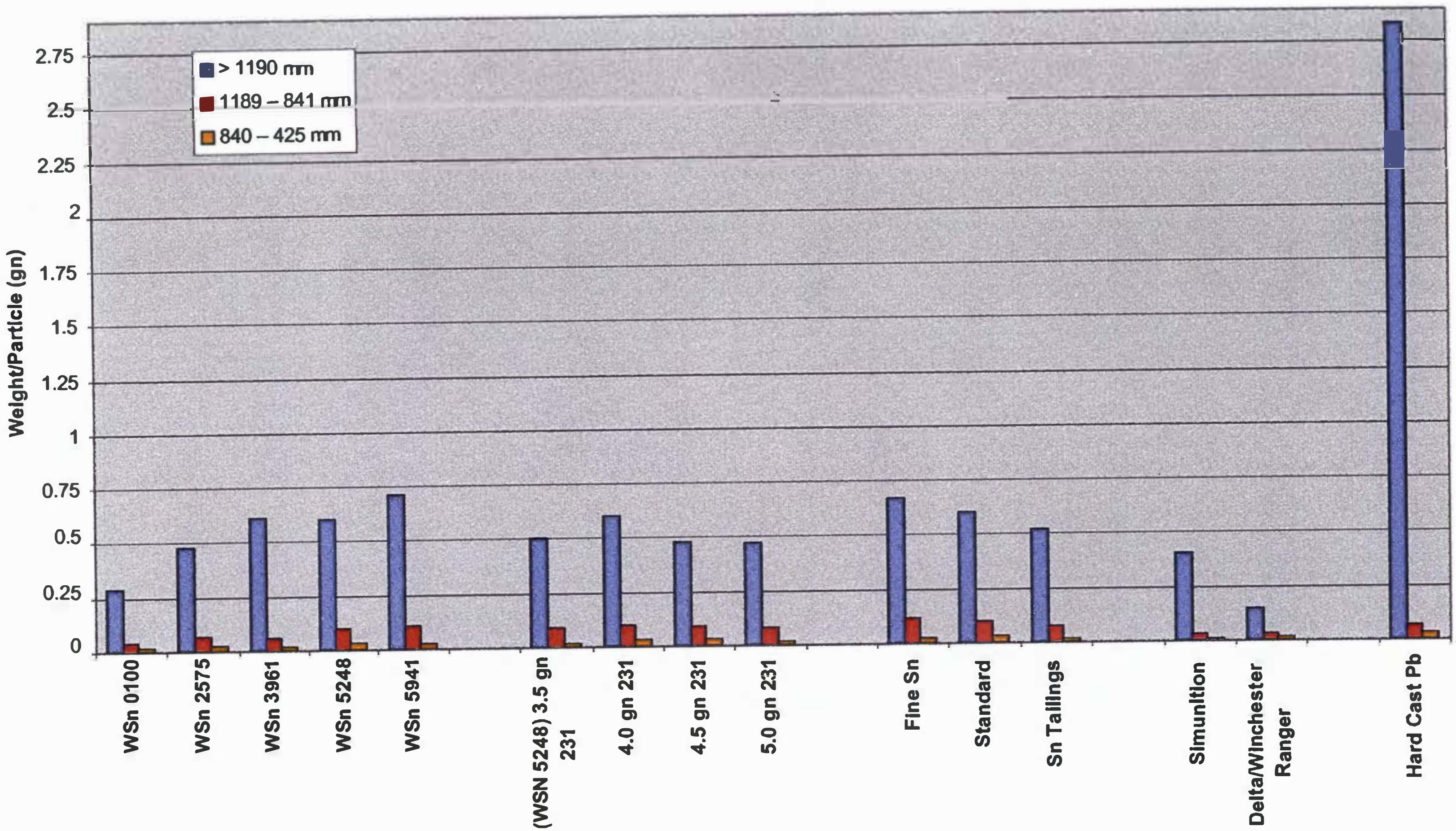


Figure 33. Particle Capture Weight

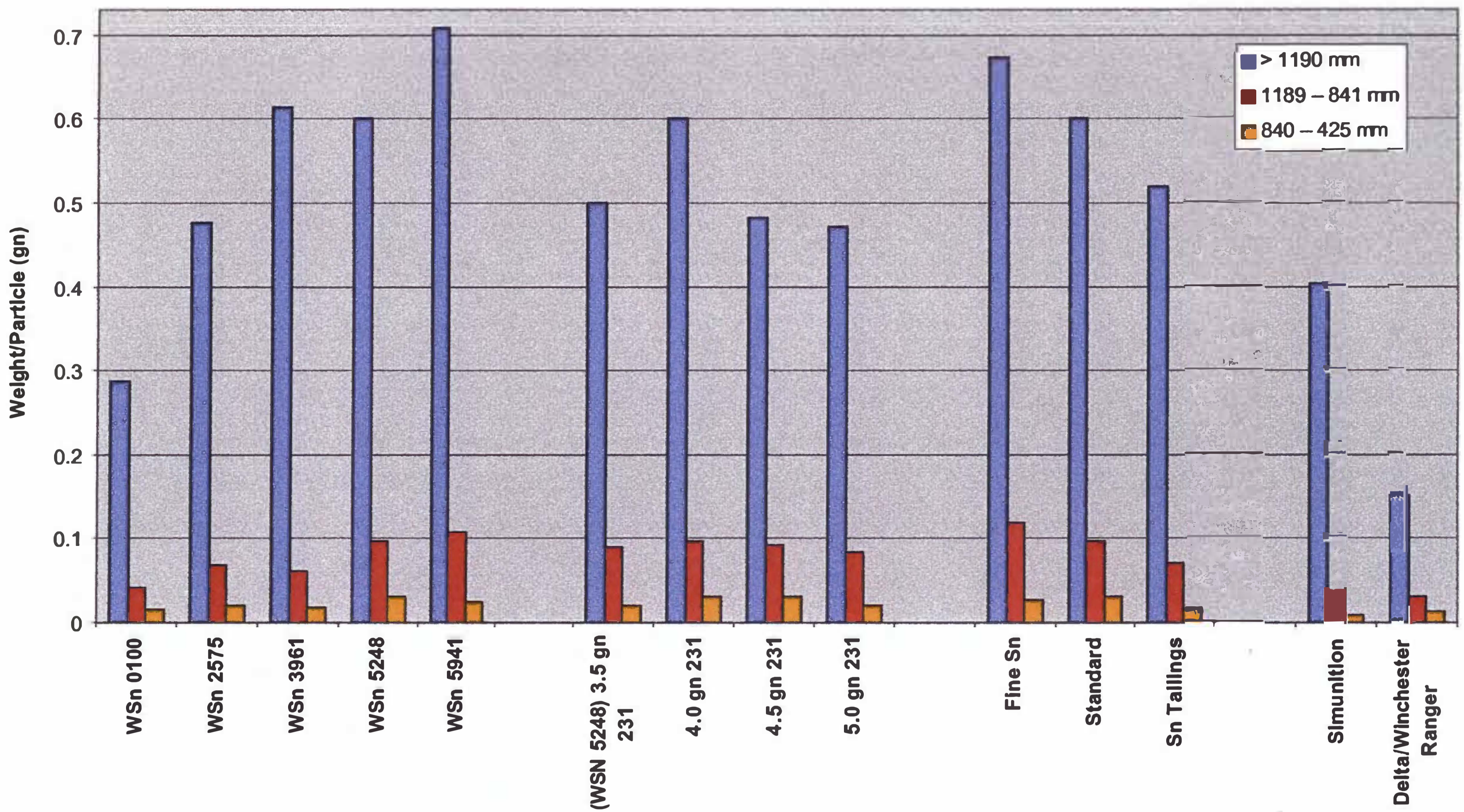


Figure 34. Particle Capture Weight (No Pb)

CHAPTER III

RESULTS

RESULTS ENERGIES AND VELOCITIES

1018 Steel Plate Velocities

Tests were conducted on a number of non-lead frangible projectiles and two lead projectiles. Velocities were taken with a chronograph near the point of impact, during the steel plate test. Kinetic energy was calculated using the average velocities with the equation: KE = ½ Mass x Velocity^2.

Figure 35 shows the average bullet velocities for the 1018 steel plate penetration test, with standard deviations included for the different mass bullets. This information is also given in Table 3 (pg. 38) for all the bullets tested in this thesis. The WSn 0100 bullet had an average velocity of 939.2 fps with a standard deviation of 45.54 fps. The WSn 2575 bullet had an average velocity of 967.1 fps with a standard deviation of 32.30 fps. The WSn 3961 bullet had an average velocity of 935.9 fps with a standard deviation of 16.40 fps. The WSn 5248 bullet had an average velocity of 987.1 fps with a standard deviation of 19.58 fps. The WSn 5941 bullet had an average velocity of 1022.0 fps with a standard deviation of 197.0 fps.

Figure 36 represents the average velocities of the different velocity group. The WSn 5248 3.5 gn 231 bullet had an average velocity of 881.4 fps with a standard deviation of 26.80 fps. The WSn 5248 4.0 gn 231 bullet had an average velocity of 970.7 fps with a standard deviation of 13.19 fps. The WSn 5248 4.5 gn 231 bullet had an average velocity of 1064.5 fps with a standard deviation of 16.97 fps. The WSn 5248 5.0

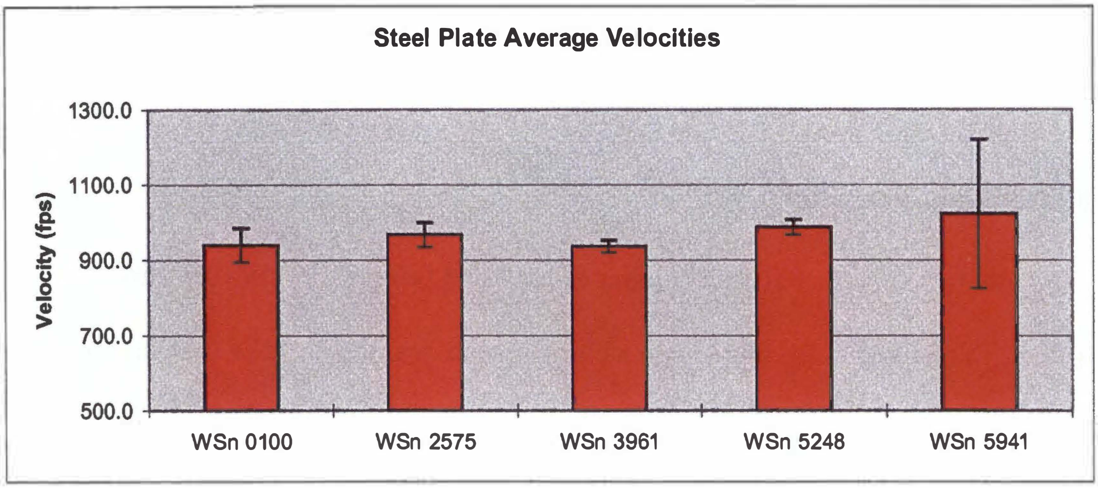


Figure 35. Steel Plate Average Velocity: Vary Energy

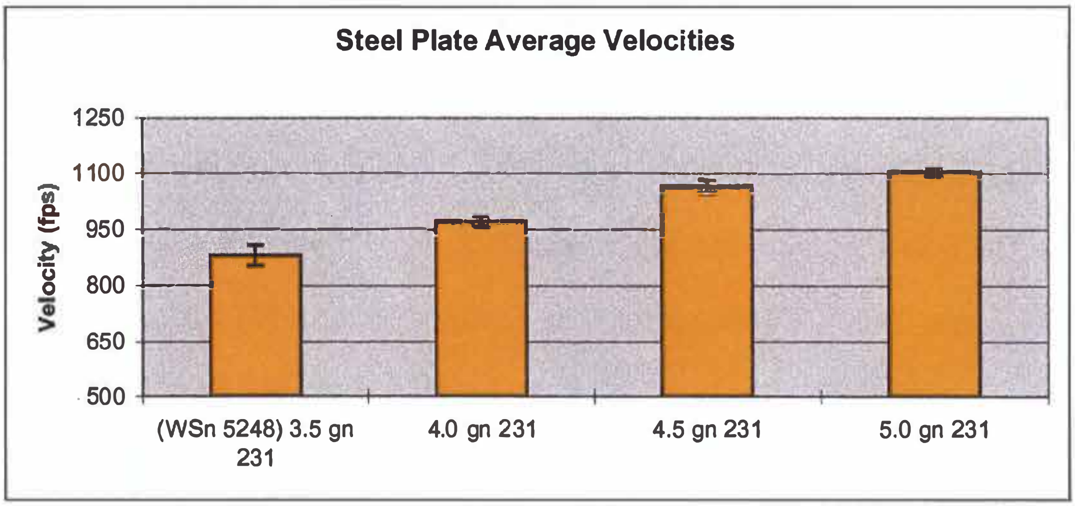


Figure 36. Steel Plate Average Velocity: Vary Velocity

gn 231 bullet had an average velocity of 1104.9 fps with a standard deviation of 10.64 fps.

Figure 37 represents the average velocities for the 1018 steel plate test for the different binder group. The WSn 5248 Fine Sn had an average velocity of 1152.0 fps with a standard deviation of 11.8 fps. The WSn 5248 Standard Sn had an average velocity of 968.3 fps with a standard deviation of 50.8 fps. The WSn 5248 Sn Tailings had an average velocity of 964.4 fps with a standard deviation of 29.0 fps.

Figure 38 represents the average velocities of the commercially frangible ammunition tested during the 1018 steel plate test. The Simunition had an average velocity of 1393.8 fps with a standard deviation of 11.08 fps. The Delta/Winchester Ranger had an average velocity of 1363.5 with a standard deviation of 24.75 fps.

Figure 39 represents the average velocities of the two non-jacketed lead rounds tested during the 1018 steel plate test. The Swaged Pb bullet had an average velocity of 1062.9 fps with a standard deviation of 9.24 fps. The Hard Cast Pb bullet had an average velocity of 1042.5 fps with a standard deviation of 29.64 fps.

1018 Steel Plate Kinetic Energy

Figure 40 represents the 1018 steel plate kinetic energy for the different mass bullets. These values are also given in Table 4 for all of the bullets tested. The standard deviations are the same as the velocity graph represented above, since the velocities were the only factor that attributed to different values calculated for the kinetic energy.

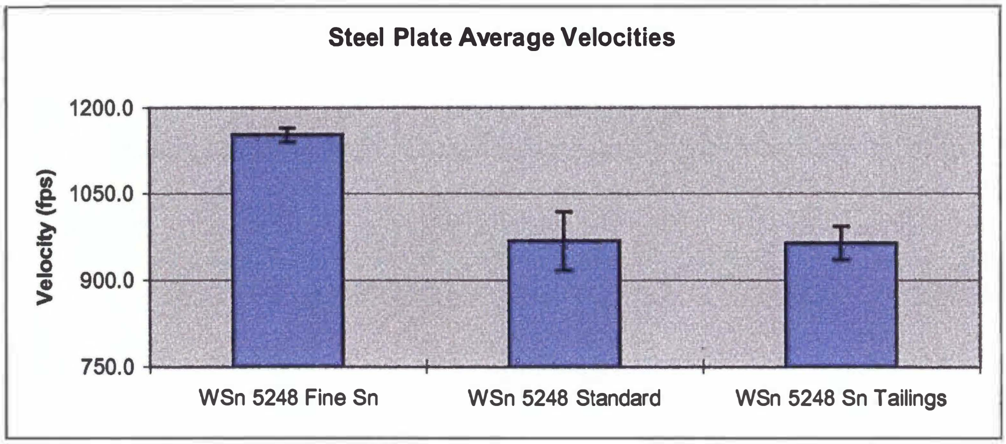


Figure 37. Steel Plate Average Velocity: Different Binders

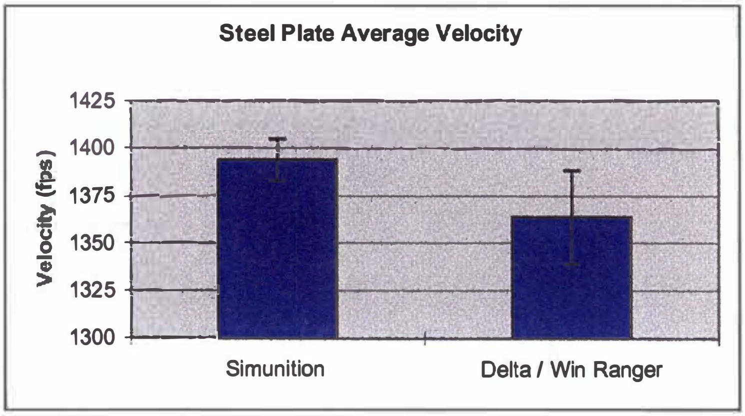


Figure 38. Steel Plate Average Velocity: Commercial Frangible Ammunition

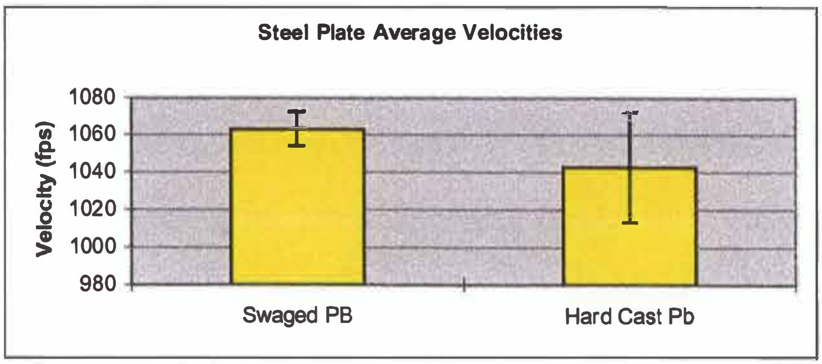


Figure 39. Steel Plate Average Velocity: Lead Rounds

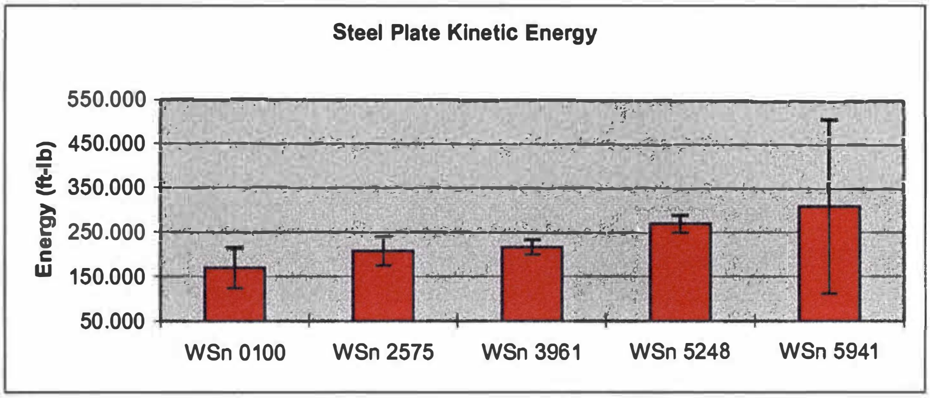


Figure 40. Steel Plate Kinetic Energy: Vary Energy

The WSn 0100 bullet had a kinetic energy of 168.651 ft-lb. The WSn 2575 bullet had a kinetic energy value of 206.783 ft-lb. The WSn 3961 bullet had a kinetic energy value of 216.203 ft-lb. The WSn 5248 bullet had a kinetic energy value of 268.576 ft-lb. The WSn 5941 bullet had a kinetic energy value of 307.708 ft-lb.

Figure 41 represents the steel plate kinetic energy of the different velocity group tested. As stated above standard deviations are the same as the average velocity group. The WSn 5248 3.5 gn 231 bullet had a kinetic energy value of 214.137 ft-lb. The WSn 5248 4.0 gn 231 bullet had a kinetic energy value of 259.726 ft-lb. The WSn 5248 4.5 gn 231 bullet had a kinetic energy value of 312.346 ft-lb. The WSn 5248 5.0 gn 231 bullet had a kinetic energy value of 336.504 ft-lb.

Figure 42 represents the kinetic energy for the different binder group during the 1018 steel plate test. The WSn 5248 Fine Sn had a kinetic energy value of 365.805 ft-lb. The WSn 5248 Standard Sn had a kinetic energy value of 258.443 ft-lb. The WSn 5248 Sn Tailings had a kinetic energy value of 256.365 ft-lb.

Figure 43 represents the kinetic energy of the commercially frangible rounds tested during the 1018 steel plate test. The Simunition bullet had a kinetic energy value of 367.065 ft-lb. The Delta/Winchester Ranger bullet had a kinetic energy value of 343.014 ft-lb.

Figure 44 represents the kinetic energy of the two non-jacketed lead rounds tested during the 1018 steel plate test. The Swaged Pb bullet had a kinetic energy value of 311.408 ft-lb. The Hard Cast Pb bullet had a kinetic energy value of 301.985 ft-lb.

RESULTS: IMPACT DAMAGE/ CRATERS

Penetration Depth

After firing the rounds at the 1018 steel plates, the plates were taken back to ORNL to be analyzed using the Rodenstock RM600 non-contact laser profilometer.

Figure 45 represents the average penetration depth of the different mass bullets on the 1018 steel plate. Values for all bullets tested are also given in Table 5. The WSn 0100 bullet had an average penetration depth of 167.3 microns with a standard deviation of 12.2 microns. The WSn 2575 bullet had an average penetration depth of 210.1 microns with a standard deviation of 34.2 microns. The WSn 3961 bullet had an average penetration depth of 212.0 microns with a standard deviation of 30.5 microns. The WSn 5248 bullet had an average penetration depth of 314.5 microns with a standard deviation of 26.6 microns. The WSn 5941 bullet had an average penetration depth of 331.91 microns with a standard deviation of 39.1 microns.

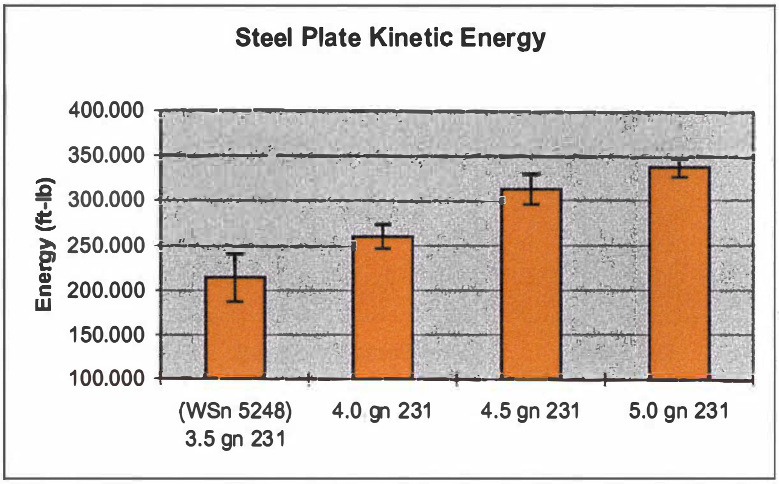


Figure 41. Steel Plate Kinetic Energy: Vary Velocity

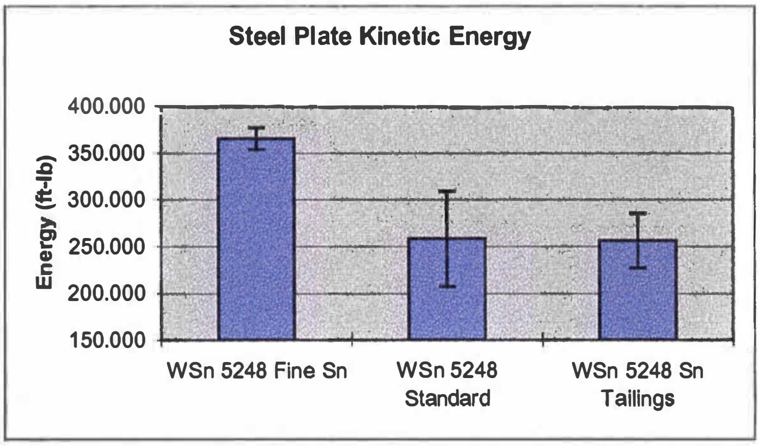


Figure 42. Steel Plate Kinetic Energy: Different Binders

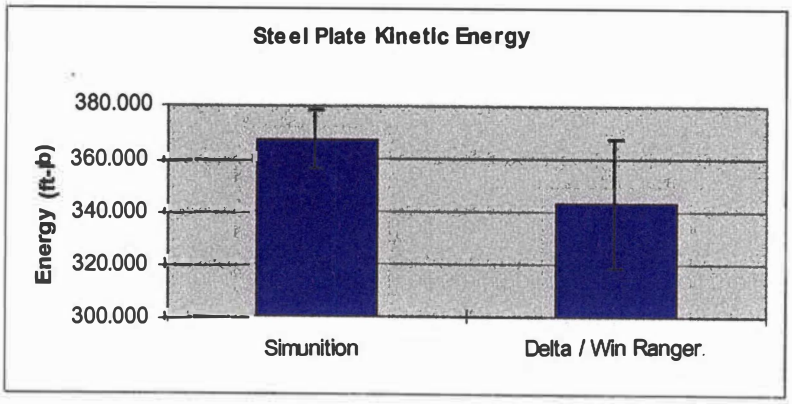


Figure 43. Steel Plate Kinetic Energy: Commercial Frangible Ammunition

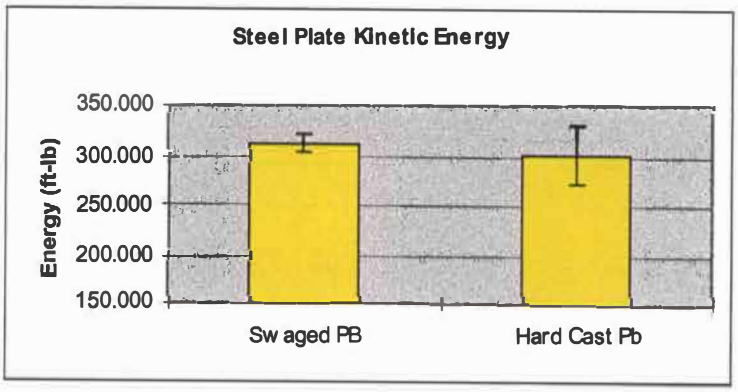


Figure 44. Steel Plate Kinetic Energy: Lead Rounds

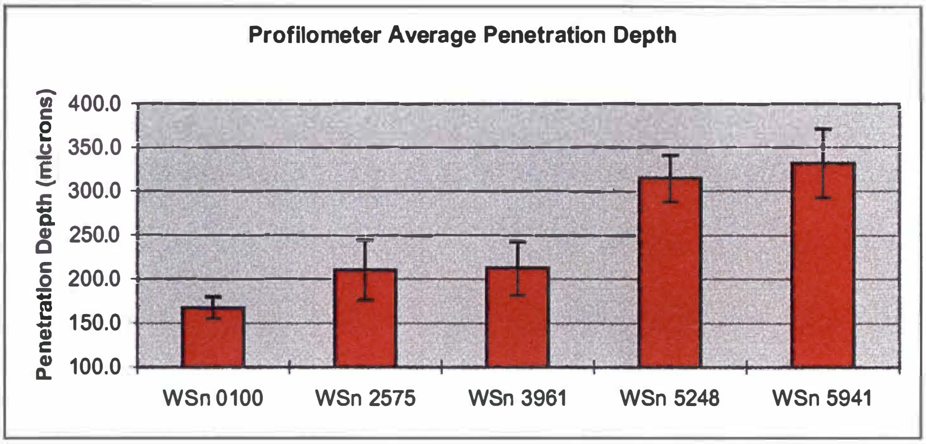


Figure 45. Profilometer Penetration Depth: Vary Energy

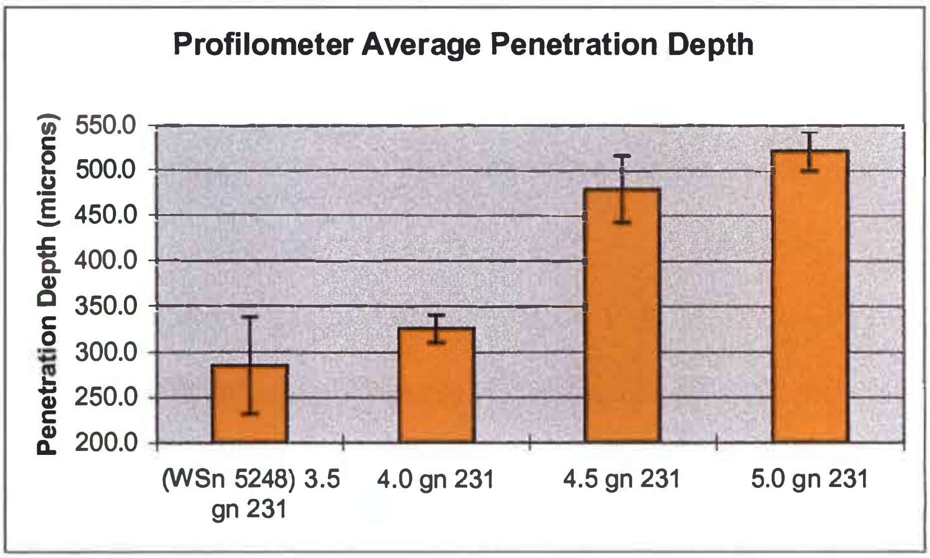


Figure 46. Profilometer Penetration Depth: Vary Velocity

Figure 46 represents the average penetration depth of the different velocity group during the 1018 steel plate test. The WSn 5248 3.5 gn 231 bullet had an average penetration depth of 285.2 microns with a standard deviation of 53.2 microns. The WSn 5248 4.0 gn 231 bullet had an average penetration depth of 325.2 microns with a standard deviation of 15.0 microns. The WSn 5248 4.5 gn 231 bullet had an average penetration depth of 479.5 microns with a standard deviation of 37.4 microns. The WSn 5248 5.0 gn 231 bullet had an average penetration depth of 521.3 microns with a standard deviation of 22.2 microns.

Figure 47 represents the average penetration depth of the different binder group. The WSn 5248 Fine Sn had an average penetration depth of 392.4 microns with a standard deviation of 53.4 microns. The WSn 5248 Standard Sn had an average penetration depth of 308.0 microns with a standard deviation of 34.9 microns. The WSn 5248 Sn Tailings had an average penetration depth of 227.6 microns with a standard deviation of 49.3 microns.

Figure 48 represents the average penetration depth of the commercially frangible ammunition tested. The Simunition bullet had an average penetration depth of 303.1 microns with a standard deviation of 19.1 microns. The Delta/Winchester Ranger bullet had an average penetration depth of 286.5 microns with a standard deviation depth of 24.4 microns.

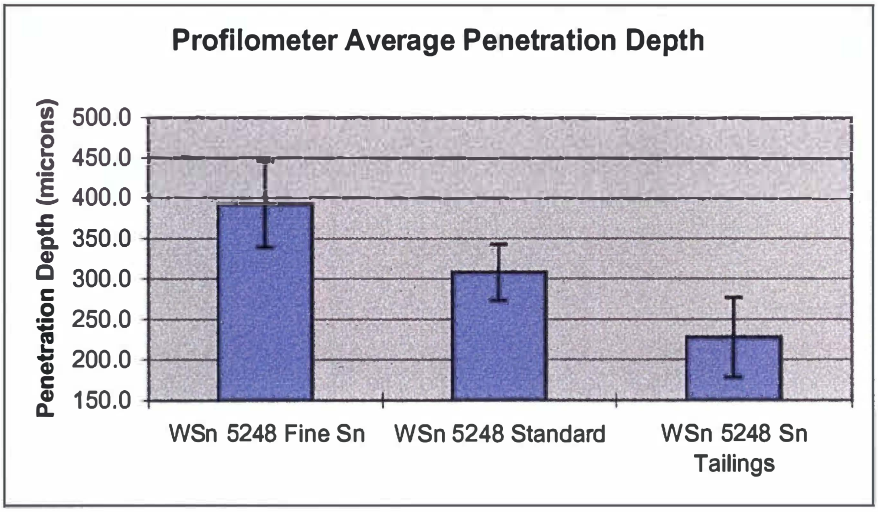


Figure 47. Profilometer Penetration Depth: Different Binders

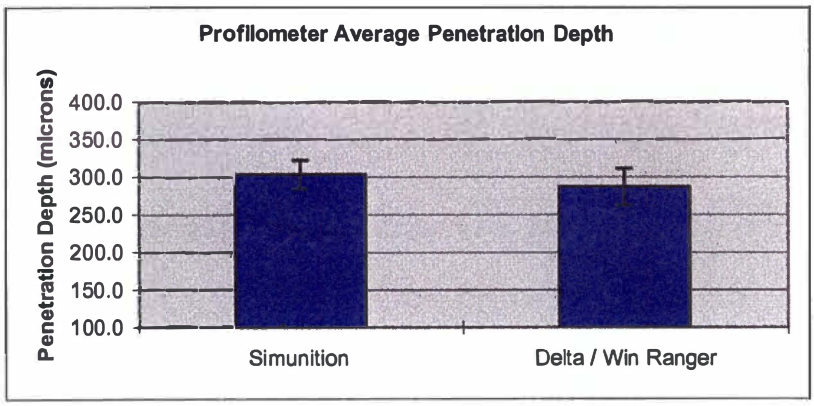


Figure 48. Profilometer Penetration Depth: Commercial Frangible Ammunition

Figure 49 represents the average penetration depth of the two non-jacketed lead bullets tested. The Swaged Pb bullet had an average penetration depth of 346.4 microns with a standard deviation of 42.3 microns. The Hard Cast Pb bullet had an average penetration depth of 300.4 microns with a standard deviation of 21.4 microns.

Profilometer Area

Figure 50 represents the profilometer area of the impact craters caused by the different mass bullets during the 1018 steel plate test. This information is also presented in Table 5 for all bullets tested. The WSn 0100 bullet had an average area of 0.41 X 10^6 μm^2 with a standard deviation of 0.08 X 10^6 μm^2. The WSn 2575 bullet had an average area of 0.60 X 10^6 μm^2 with a standard deviation of 0.11 X 10^6 μm^2. The WSn 3961 bullet had an average area of 0.75 X 10^6 μm^2 with a standard deviation of 0.13 X 10^6 μm^2. The WSn 5248 bullet had an average area of 1.01 X 10^6 μm^2 with a standard deviation of 0.16 X 10^6 μm^2. The WSn 5941 bullet had an average area of 1.12 X 10^6 μm^2 with a standard deviation of 0.15 X 10^6 μm^2.

Figure 51 represents the different velocity group tested. The WSn 5248 3.5 gn 231 bullet had an average area of 0.90 X 10^6 μm^2 with a standard deviation of 0.26 X 10^6 μm^2. The WSn 5248 4.0 gn 231 bullet had an average area of 1.06 X 10^6 μm^2 with a standard deviation of 0.10 X 10^6 μm^2. The WSn 5248 4.5 gn 231 bullet had an average area of 1.90 X 10^6 μm^2 with a standard deviation of 0.23 X 10^6 μm^2. The WSn 5248 5.0 gn 231 bullet had an average area of 2.16 X 10^6 μm^2 with a standard deviation of 0.23 X 10^6 μm^2.

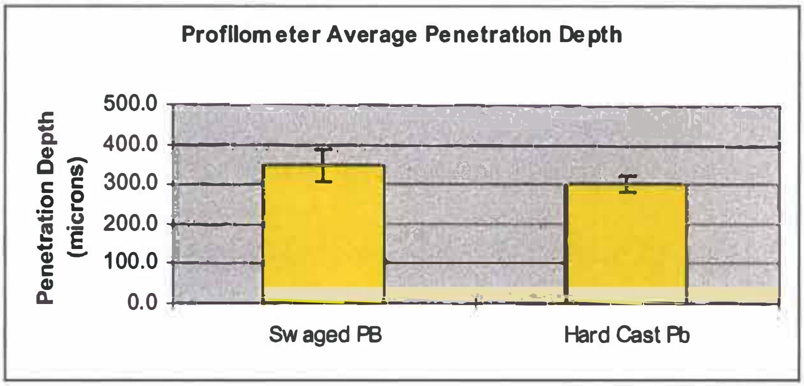


Figure 49. Profilometer Penetration Depth: Lead Rounds

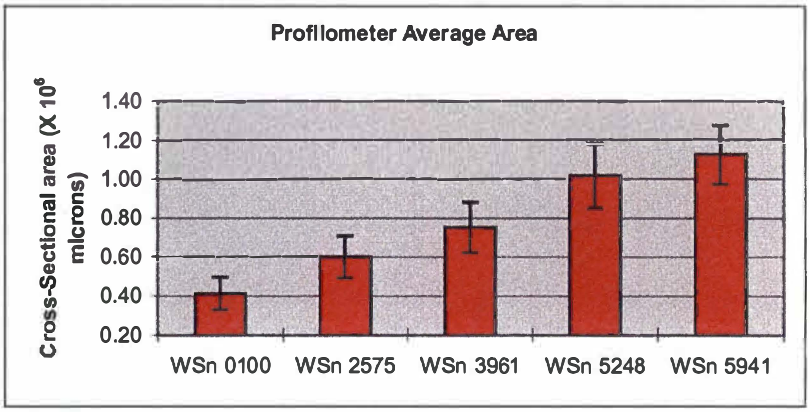


Figure 50. Profilometer Average Area: Vary Energy

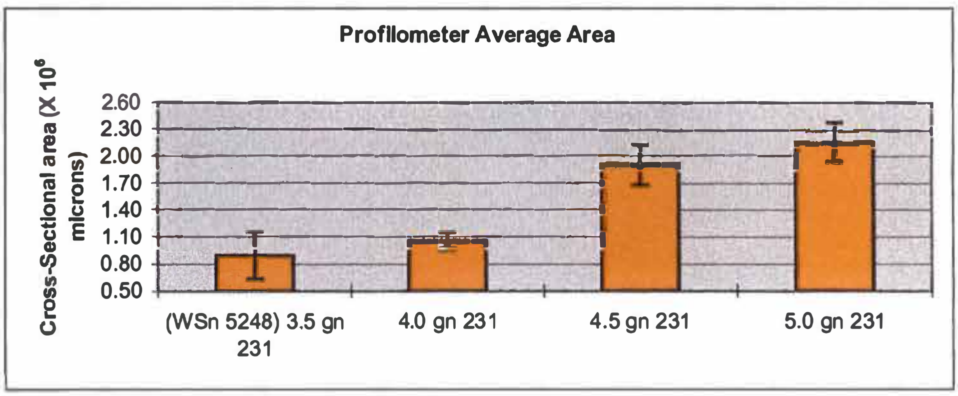


Figure 51. Profilometer Average Area: Vary Velocity

Figure 52 represents the different binder group tested. The WSn 5248 Fine Sn bullet had an average area of 1.34 X 10^6 μm^2 with a standard deviation of 0.24 X 10^6 μm^2. The WSn 5248 Standard Sn bullet had an average area of 0.94 X 10^6 μm^2 with a standard deviation of 0.19 X 10^6 μm^2. The WSn 5248 Sn Tailings bullet had an average area of 0.62 X 10^6 μm^2 with a standard deviation of 0.20 X 10^6 μm^2.

Figure 53 represents the commercially frangible ammunition tested. The Simunition bullet had an average area of 1.13 X 10^6 μm^2 with a standard deviation of 0.10 X 10^6 μm^2. The Delta/Winchester Ranger bullet had an average area of 1.06 X 10^6 μm^2 with a standard deviation of 0.12 X 10^6 μm^2.

Figure 54 represents the two non-jacketed lead bullets tested. The Swaged Pb bullet had an average area of 1.46 X 10^6 μm^2 with a standard deviation of 0.44 X 10^6 μm^2. The Hard Cast Pb bullet had an average area of 0.97 X 10^6 μm^2 with a standard deviation of 0.08 X 10^6 μm^2.

RESULTS: FRAGMENTS

To determine the frangibility of the bullets tested, bullets were fired at a hardened steel plate (AR400) with a donut gelatin ring attached. The bullets were fired into the plate through a hole in the gelatin and the fragments were captured upon impact. The gelatin was taken back to ORNL and melted down and poured through a series of sieves to capture the fragments of the bullets tested. The WSn 0100 bullet had 24.70 % of it's total weight captured in the first sieve, 4.16 % captured in the second sieve, 9.73 % captured in the third sieve, 4.34 % captured in the fourth sieve, and 57.07 % turning into dust. The WSn 2575 bullet had 28.61 % captured in the first sieve, 8.36 % captured in

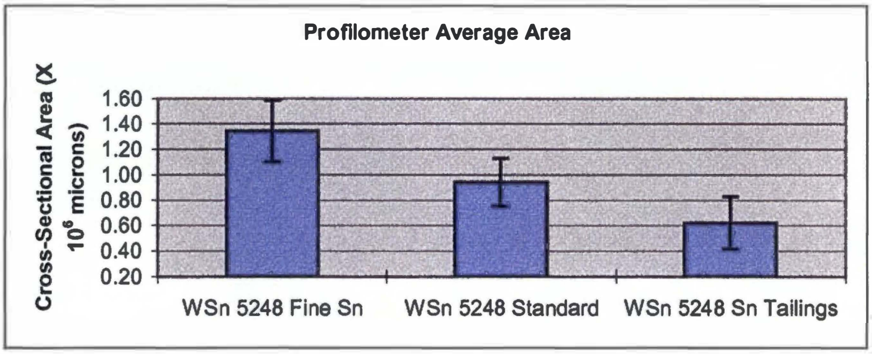


Figure 52. Profilometer Average Area: Different Binders

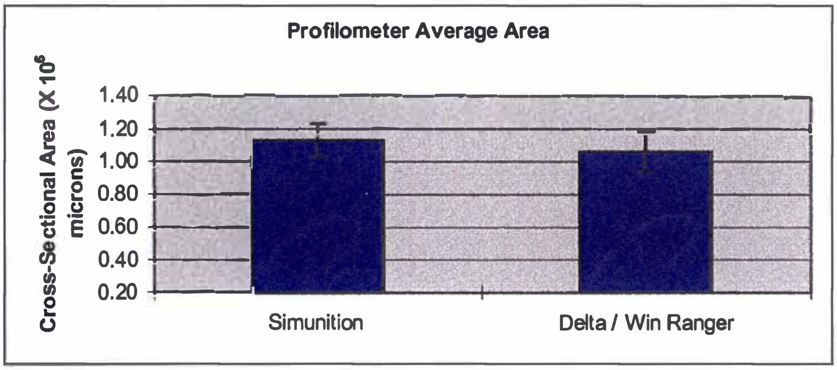


Figure 53. Profilometer Average Area: Commercial Frangible Ammunition

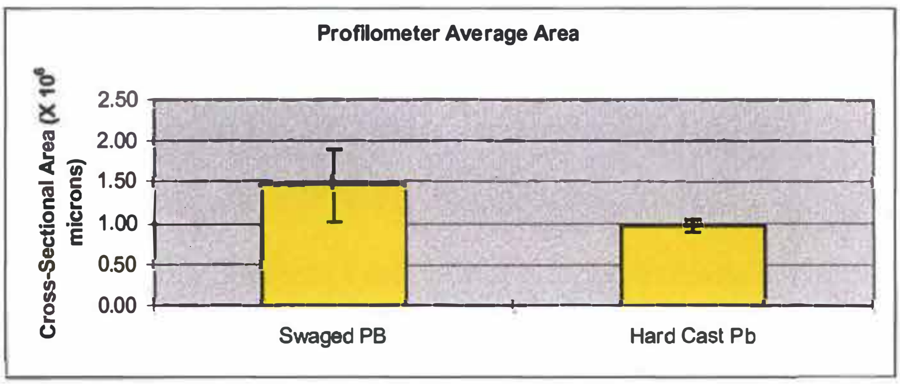


Figure 54. Profilometer Average Area: Lead Rounds

the second sieve, 9.83 % captured in the third sieve, 2.95 % captured in the fourth sieve, and 50.26 % turning into dust. The WSn 3961 bullet had 28.94 % captured in the first sieve, 5.85 % captured in the second sieve, 8.36 % captured in the third sieve, 2.24 % captured in the fourth sieve, and 54.60 % turning into dust.

Figure 55 shows the WSn 5248 bullet had 27.09 % captured in the first sieve, 6.74 % captured in the second sieve, 10.60 % captured in the third sieve, 2.71 % captured in the fourth sieve, and 52.85 % captured in the fourth sieve. The WSn 5941 bullet had 24.05 % captured in the first sieve, 6.37 % captured in the second sieve, 9.97 % captured in the third sieve, 2.78 % captured in the fourth sieve, and 56.83 % turning into dust. Table 9 shows the weight per particle for the vary energy group.

Figure 56 shows the 3.5 gn 231 bullet had 22.04 % of it's total weight recovered in the first sieve, 5.59 % captured in the second sieve, 7.80 % captured in the third sieve, 1.90 % captured in the fourth sieve, and 62.87 % turning into dust. The 4.0 gn 231 bullet had 27.09 % captured in the first sieve, 6.74 % captured in the second sieve, 10.60 % captured in the third sieve, 2.71 % captured in the fourth sieve, and 52.85 % turning into dust. The 4.5 gn 231 bullet had 12.38 % captured in the first sieve, 5.21 % captured in the second sieve, 8.61 % captured in the third sieve, 2.88 % captured in the fourth sieve, and 70.92 % turning into dust. The 5.0 gn 231 bullet had 6.57 % captured in the first sieve, 3.27 % captured in the second sieve, 5.21 % captured in the third sieve, 1.85 % captured in the fourth sieve, and 83.10 % turning into dust. Table 10 shows the weight per particle for the vary velocity group.

Figure 57 shows the WSn 5248 with Fine Sn had 20.07 % captured in the first sieve, 7.96 % captured in the second sieve, 12.90 % captured in the third sieve, 2.63 % captured in

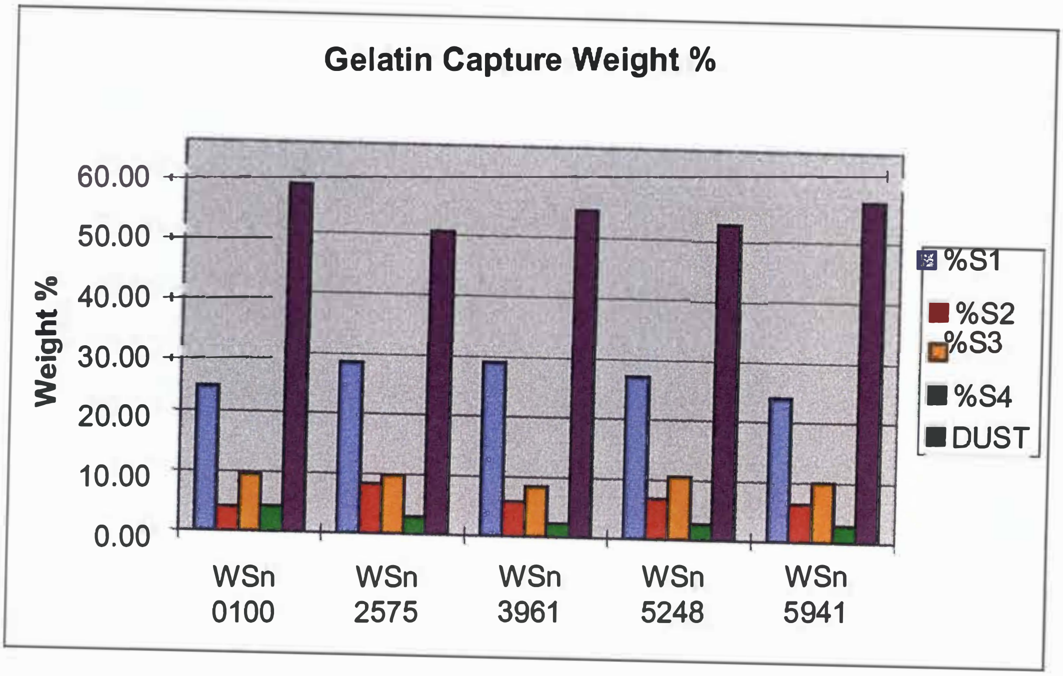


Figure 55. Gelatin Capture Weight %: Vary Energy

Table 9. **Weight per Particle: Vary Energy**

Bullet Type	Weight/Particle (gn) > 1190 µm	1189 – 841 µm	840 – 425 µm
Vary Energy (mass)			
WSn 0100	.2863	.0421	.0160
WSn 2575	.4756	.0690	.0207
WSn 3961	.6147	.0618	.0182
WSn 5248	.6013	.0973	.0307
WSn 5941	.7087	.1067	.0240

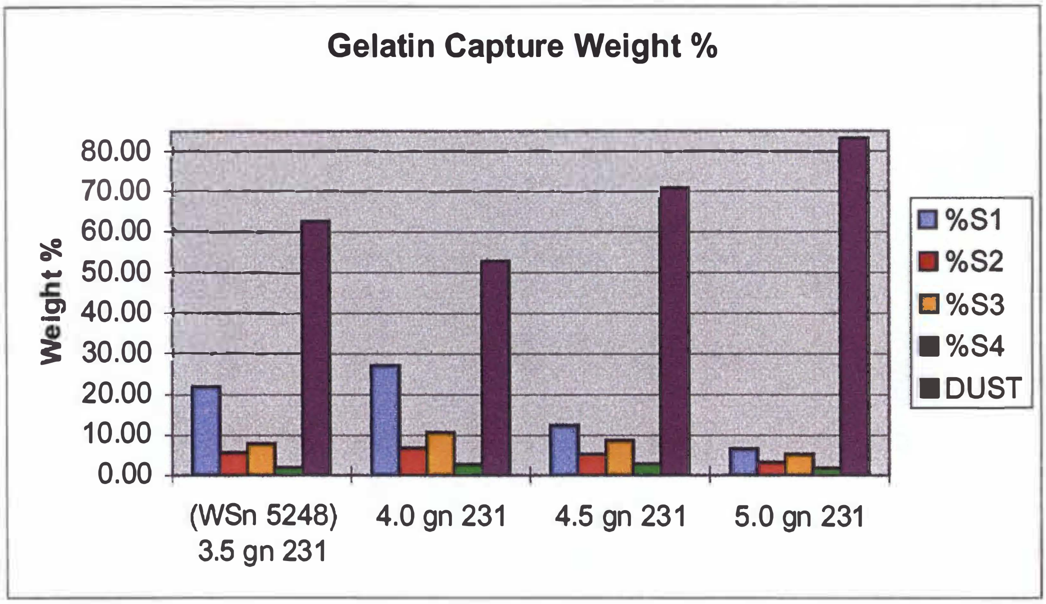


Figure 56. Gelatin Capture Weight %: Vary Velocity

Table 10. **Weight Per Particle: Vary Velocity**

	Weight/Particle (gn)		
Bullet Type	**> 1190 μm**	**1189 – 841 μm**	**840 – 425 μm**
Vary Velocity			
(WSn 5248) 3.5 gn 231	.5005	.0893	.0200
4.0 gn 231	.6013	.0973	.0307
4.5 gn 231	.4829	.0920	.0307
5.0 gn 231	.4713	.0827	.0200

the fourth sieve, and 56.44 % turning into dust. The WSn 5248 Standard had 27.09 % captured in the first sieve, 6.74 % captured in the second sieve, 10.60 % captured in the third sieve, 2.71 % captured in the fourth sieve, and 52.85 % turning into dust. The WSn 5248 with Sn Tailings had 11.78 % captured in the first sieve, 4.12 % captured in the second sieve, 8.88 % captured in the third sieve, 3.57 % captured in the fourth sieve, and 71.65 % turning into dust. Table 11 shows the weight per particle for the different binders group.

Figure 58 shows the Simunition bullet had 28.73 % captured in the first sieve, 11.35 % captured in the second sieve, 25.00 % captured in the third sieve, 6.99 % captured in the fourth sieve, and 27.93 % turning into dust. The Delta/Winchester Ranger bullet had 44.19 % captured in the first sieve, 12.78 % captured in the second sieve, 16.96 % captured in the third sieve, 3.58 % captured in the fourth sieve, and 22.49 % turning into dust. Table 12 shows the weight per particle for commercially frangible ammunition group.

Only the Hard Cast Pb bullet was captured due to time constraints. Figure 59 shows the Hard Cast bullet had 54.25 % captured in the first sieve, 0.79 % captured in the second sieve, 0.56 % captured in the third sieve, 0.06 % captured in the fourth sieve, and 44.33 % turning into dust. The Hard Cast Pb round had the highest weight per particle due to large fragments recovered as shown in Table 13

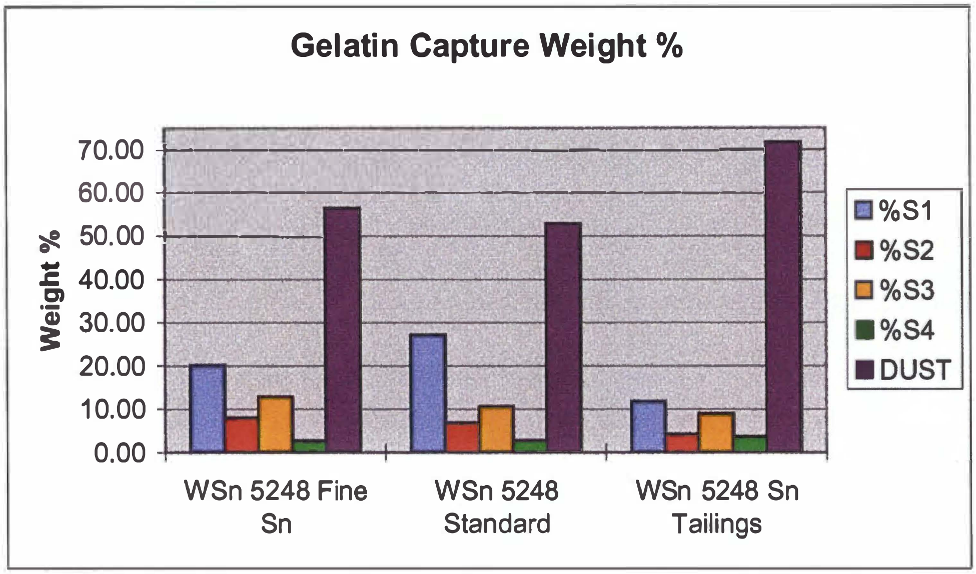


Figure 57. Gelatin Capture Weight %: Different Binders

Table 11. **Weight Per Particle: Different Binders**

	Weight/Particle (gn)		
Bullet Type	**> 1190 μm**	**1189 – 841 μm**	**840 – 425 μm**
Different Binders			
Fine Sn	.6733	.1187	.0267
Standard	.6013	.0973	.0307
Sn Tailings	.5187	.0707	.0147

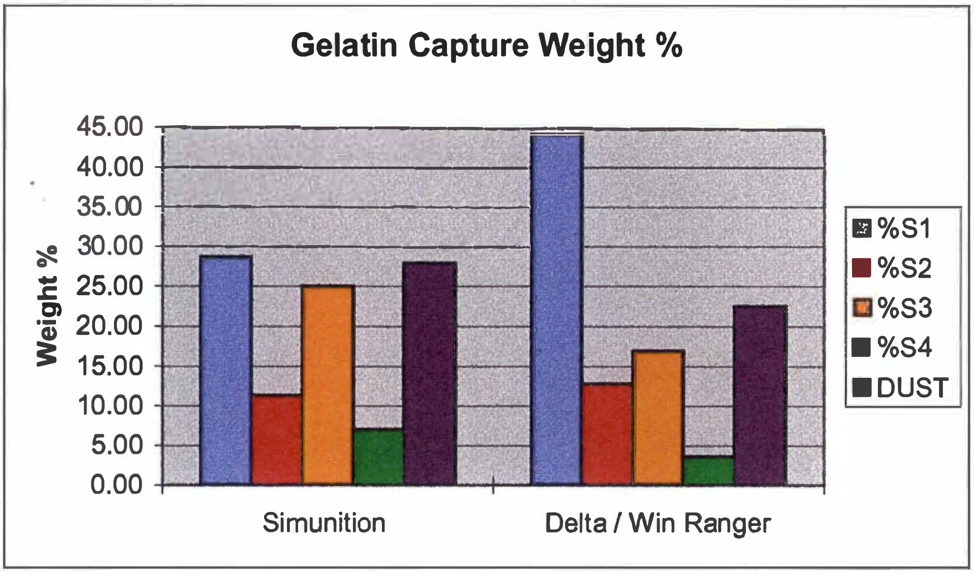


Figure 58. Gelatin Capture Weight %: Commercial Frangible Ammunition

Table 12. **Weight Per Particle: Commercial Frangible Ammunition**

	Weight/Particle (gn)		
Bullet Type	**> 1190 μm**	**1189 – 841 μm**	**840 – 425 μm**
Commercially Frangible Ammunition			
Simunition	.4039	.0343	.0080
Delta/Winchester Ranger	.1514	.0305	.0133

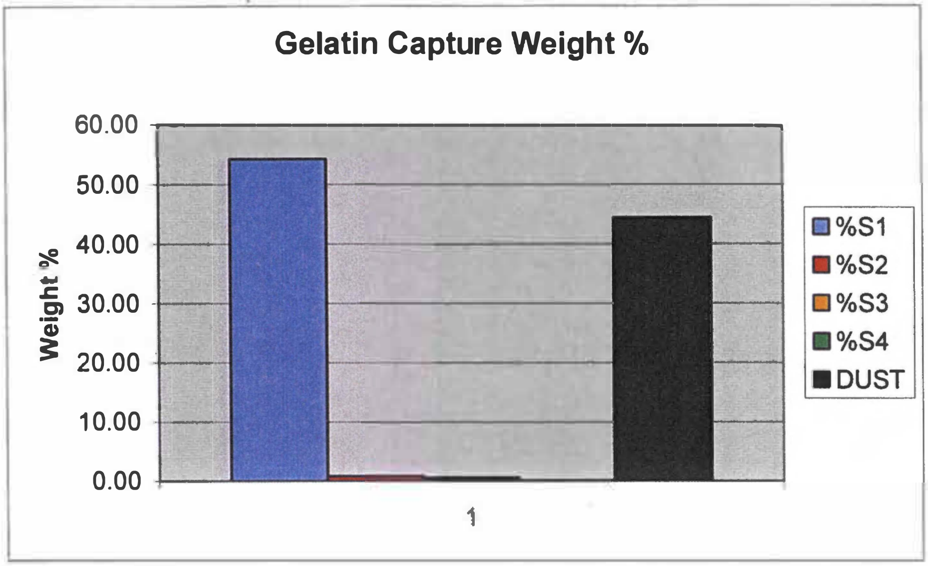


Figure 59. Gelatin Capture Weight %: Lead Rounds

Table 13. **Weight Per Particle: Lead Rounds**

	Weight/Particle (gn)		
Bullet Type	**> 1190 μm**	**1189 – 841 μm**	**840 – 425 μm**
Lead Rounds			
Hard Cast Pb	2.8319	.0627	.0347

CHAPTER IV

CONCLUSIONS

Trying to describe damage done by the different bullets used in this experiment, was a daunting task. Before arriving at any conclusions, one has to look at all the pieces. During the course of this work, tests were conducted that examined the bullet and target interaction.

In looking at the bullet characteristics, changes were made in weight, energy, composition, etc., which gave unique trends and data. Targets were shot and analyzed for penetration depth and cross-sectional area. This data helped to give a quantifiable value for frangibility.

Another key part of frangibility is the fragments generated upon the bullet's impact. The fragment test shows a viable and documentable value for frangibility. The trade off between size of particles and damage to the target is the key to a successful frangible bullet.

This study has shown people in government and industry a new way to quantify frangibility. By using new methods of evaluating and testing frangible ammunition, this research has opened the door to a new thought process and procedures for future testing.

RECOMMENDATIONS

Future research in non-lead frangible bullets should focus on a limited number of bullets. By limiting the number of bullets tested, a more detailed design of experiments can be achieved. This would allow a user to focus on one or two changes in bullet characteristics, and gain more statistical data by more repetition and number of trials for each test. It would be interesting to see future tests conducted with a couple of bullets and a large number of targets, ranging from concrete, heavy pane glass, etc.

LIST OF REFERENCES

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1. Morehouse, K. "Lead Poisoning of migratory birds: the U.S. Fish and Wildlife Service position.." D.J. Pain (ed.) Lead poisoning in waterfowl. Slimbridge, U.K.: IWRB Spec. Publ. No. 16, pp. 51-55.

2. Ordija, V. "Lessons from Lordship." National Shooting Range Symposium Proceedings, Salt Lake City, Utah, 17-19 October 1993, pp. 73-79.

3. SAAMI (Sporting Arms and Ammunition Manufacturing Institute). "Summary of relevant case law relating to shooting ranges." Newtown, Conn., 1993.

4. Yurdin, B.J. "An investigation of Lake Michigan sediment at the Lincoln Park Gun Club, Chicago, Illinois." Watershed Unit, Permit Section, Division of Water Pollution Control, Illinois Environmental Protection Agency, 1993.

5. Anania, Thomas L, Joseph A. Seta. Lead Exposure and Design Considerations for Indoor Firing Ranges. Cincinnati, Ohio: NIOSH 76-130, 1975.

6. National Research council Committee on biologic Effects of Atmospheric Pollutants. Lead: Airborne lead in perspective. Washington, D.C.: National Academy of Sciences, 1972.

7. Juhasz, A.A. Reduction of Airborne Lead in Indoor Firing Ranges by Using Modified Ammunition. Washington, D.C.: National Bureau of Standards Pub. 480-26, 1977.

8. Sever, C. "Lead and outdoor ranges." National Shooting Range Symposium Proceedings, Salt Lake City, Utah, 17-19 October 1993, pp. 87-94.

9. Simmons, Morgan. "EPA Proposes to Ban Lead and Zinc Sinkers," *Knoxville News-Sentinel,* 13 March 1994, p. C10.

10. Edwards, Michael, http://www.nesportsman.com/news/news5.shtml. This page last updated Thursday June 15 2000.

11. http://www.shelfspace.com/~c-r-ffl/archives/199501/msg00033.html. Gun Owner's of America, 8001 Forbes Place, Suite 102 Springfield VA 22151 (703) 321-8585

12. Brezny, L. P. "Polymer/Tungsten Shot," Handloaders Shotgun, Special Edition 1992, pp. 30-34.

13. Brister, B. "Super Shot," Field and Stream, November 1990, pp. 76-80.

14. Jackson, T. "Glimmer of hope." Shooting Times and Country Magazine. 15-21 September 1994, pp. 10-12.

15. Friberg, L., J. Lener. "Molybdenum," Handbook on the toxicity of metals. 2nd edition. New York, Elsevier Science publishers B.V., 1986.

16. Marchington, J. "Plastic Fantastic?" Shooting Times and Country Magazine. 1-7 December 1994, p. 2.

17. Fender, James. "The Steel Shot Controversy," Guns, September 1988, pp. 38-40, 58-65.

18. Steele, Kevin E. "Why Steel Shot Opposition is Growing," Guns & Ammo, October 1989, pp. 76-80.

19. Brister, B. "Steel shot: ballistics and gunbarrel effects." D.J. Pain (ed.) Lead poisoning in waterfowl. Slimbridge, U.K.: IWRB Spec. Publ. No. 16, pp. 26-28.

20. Coburn, C. "Lead poisoning in waterfowl: the Winchester perspective." D.J. Pain (ed.) Lead poisoning in waterfowl. Slimbridge, U.K.: IWRB Spec. Publ. No. 16, pp. 46-50.

21. Seyfried, Ross. "Non-Toxic Shot Breakthrough!," Guns & Ammo, December 1992, pp. 94-99, 107.

22. Forsyth, Ron. "The New Bismuth Non-Toxic Shot," The Double Gun Journal **4**(3), Autumn 1993, pp. 9-15.

23. Lowry, E. "Bismuth shot: the ballistic potential." American Rifleman, September, p. 6.

24. Beijer, Reginus. "Experiences with Zincon, A Useful reagent for the Determination of Firing Range with Respect to Lead-Free Ammunition," Journal of Forensic Science 39(4), July 1994, pp. 981-987.

25. Grandy, J.W. IV, L.N. Locke, G.E. Bagley. "Relative toxicity of lead and five proposed substitute shot types to pen-reared mallards." Journal of Wildlife Management. Issue 32(2) 1968, pp. 483-488.

26. Reece, R.L., D.B. Dickson, P.J. Burrows. "Zinc toxicity (new wire disease) in aviary birds." Australian Veterinary Journal. Issue 63 1986, p. 199.

27. Droual, R., C.U. Meteyer, F.W. Galey. "Zinc toxicosis due to ingestion of a penny in a gray-headed chachalaca (Ortalis cinerciceps). Avian Dis. Issue 37 1991, pp. 1007-1011.

28. Zdziarski, J.M., M. Mattix, R.M. Bush, R.J. Rontali. "Zinc toxicosis in diving ducks." Journal of Zoo Wildlife Medicine. Issue 25(3) 1994, pp. 438-445.

29. Ringelman, J.K., M.W. Miller, W.F. Andelt. "Effects of ingested tungsten-bismuth-tin shot on captive mallards." Journal of Wildlife Management. Issue 57 1993, pp. 725-732.

30. Isserow, S. "Ordnance Applications," Metals Handbook, Ninth Edition, *Volume 7: Powder Metallurgy*, Metals Park, Ohio: American Society for Metals, 1984, pp. 679-695.

31. Penrice, Thomas. "Kinetic Energy Penetrators," Metals Handbook, Volume 7: Powder Metallurgy, *Powder Systems and Applications: Ordnance*, Metals Park, Ohio: American Society for Metals, 1984, pp. 688-691.

32. Winchester/Delta, Lead-free frangible ammunition, tungsten and copper in Nylon, Winchester Ammunition, 427 N. Shamrock St., East Alton, IL 62024.

33. GREEN SHIELD™, lead-free frangible ammunition, tungsten and copper in Nylon, US Patent #5,237,930 issued August 24, 1993, Simunition Technologies, 366 Bruyere Street, Ottawa, Canada K1N 5E7.

34. *New Standard Dictionary of the English Language.* 1974, 1984, 1995.

35. Williams, Stanley. "Feasibility Study: Frangible Training Ammunition 9x19mm," Naval Sea Systems Command, 27 December 1988.

36. Rose, Andrew. "Final Report for the Production Qualification Test (PQT) of the 5.56- and 9-mm Frangible Training Ammunition (Winchester)," Aberdeen Proving Ground, MD: U.S. Army Aberdeen Test Center, April 1998.

37. Hill, Jim. http://www.cnn.com/US/9703/01/bank.shootout/. Posted 1 March 1997.

38. Flinn, Richard A., Paul K. Trojan. Engineering Materials and Their Applications. Second Edition, Boston, Houghton Mifflin Company, 1981, pp. 65-87, 534-550.

39. Osram Sylvania, Chemical & Metallurgical Products, Hawes St., Towanda, PA. 18848-0504. www.sylvania.com.
40. Pyron Metal Powders, 6621 Highway 411 S., Greenback, TN 37742. www.zemex.com/zemex/metalpow.html.

41. Smith, Ted. "The Bullet Swage Manual," North Bend, Oregon: Wegferd Publications, 1976.

42. Fackler, Martin L., John A. Malinkowski, "Ordnance Gelatin for Ballistic Studies," American Journal of Forensic Medicine and Pathology 9(3): 1988, pp. 218 – 219.

43. *The American Heritage® Dictionary of the English Language, Fourth Edition* Copyright © 2000 by Houghton Mifflin Company. Published by Houghton Mifflin Company.

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